MOTION RESPONSES OF FPSO SUBJECTED TO
P-M WAVE SPECTRUM

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CIVIL ENGINEERING
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by

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Submitted to the Civil Engineering Programme

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CERTICATION OF APPROVAL

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Approved by,

(Prof Dr.Kurian V.John)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

June 2010

CERTICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SITI KHOLIJAH BINTI ABDUL GHAFFAR

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In the name of Allah, The most Gracious, The Most Merciful,

First of all, the author would like to express upmost gratitude goes to the author supervisor and advisor, Prof Dr.Kurian V.John for all his co-operation, guidance and willingness to help and assist the author from the project inception till completing of this Final Year Project. Without his invaluable insight and assistance, this project would not have been done and successfully write up.

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Special thanks to Dr.Shamsul Rahman Mohamed Kutty as the Head of Civil Engineering Department of Universiti Teknologi PETRONAS and all the supportive lecturers for their help and kindness to the successful of this project

On a personal note, the author wants to acknowledge profound gratitude to all family members for generous spirit, moral support and prayers. Not to forget, to all colleagues, thank you very much for the technical support and time. May God bless us.

ABSTRACT

Floating Production Storage and Offloading (FPSO) unit made a significant progress in technology for deep water exploration and has become a common floating structure to be used around the world. The need for a study on the hydrodynamic analysis of FPSO is important as it has to be considered in the preliminary design of the FPSO for more deepwater discoveries in the future. The dimension and environmental data were taken from FPSO Ruby II project. The dynamic analysis of the mooring lines was not incorporated in the numerical calculations to simplify the analysis of the FPSO responses. The FPSO was modeled as floating structures with three degrees of freedom; surge, heave and pitch since the vessel was subjected to uni-directional wave in surge direction. The calculation of excitation wave forces and moments acting on FPSO were difficult due to the large surface area and its complex shape. Froude Krylov theory was applied in this case since it utilized the pressure-area method for computing the wave forces acting on the structure. Frequency domain analysis was used to represent the energy distribution on sea using P-M wave spectrum and the wave motion profile was generated from the spectrum model. The dynamic analysis was performed in regular wave with maximum design wave height of 9.6 m and random wave condition of significant height of 4.9 m. The analysis showed that the frequency domain approach yielded good agreement with results of literature. Heave showed higher motion response compared to surge due to dynamic amplification. Results on pitch motion showed small responses for both regular and random wave, due to stability of the FPSO. It is very important to determine the maximum offset motion on each direction to maintain the operation of FPSO at the highest safety and most stabilize condition.

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LIST OF ABBREVIATIONS

COG : Center of Gravity

COB : Center of Buoyancy

DAF : Dynamic Amplification Factor

FPSO : Floating Production Storage Offloading

LBP : Length between Perpendicular

LCG : Longitudinal Center Gravity

LOA : Length Overall

MSL : Mean Sea Level

P-M : Pierson Moskowitz Spectrum

RAO : Response Amplitude Factor

SWL : Sea Water Level

TCG : Transverse Center Gravity

TLP : Tension Leg Platform

VCG : Vertical Center Gravity

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

As the need for oil and natural gas are increase rapidly to the world energy demand, the hydrocarbons reserve in shallow water are slowly depleting and started to diverge the interest of exploration into the deeper water depth with the range of 1000m to 3000m. The water depths and reservoir structure make exploration on deep water most technologically challenging. The installations of fixed structures are no more applicable at this water depth and the introducing of floating structures concept has enhancing the capability of hydrocarbon production at this new exploration area. According to Low, Y.M., & Langley, R.S., (2007) fixed production platforms at shallow water regions depth are no longer within a feasible range making a floating production structures design a far more economical choice. The focus on the deep water exploration makes the floating structures significantly dominance in the offshore industry up to now.

1.1.1 Floating Offshore Structure

Floating offshore structure has been introduced as an approachable design to enhance the technology in oil and gas exploration and this would be otherwise impossible for the fixed structure. Floating structures facilities are growing rapidly around the globe, with more sophisticated designs for semi-submersible platforms, tension leg platforms, spar platforms, and floating production storage and offloading (FPSO) to improve the efficiency, flexibility and capacity of the crude oil production. Floating structures basically consists of neutrally and positively buoyant structures. Neutrally buoyant structures such as FPSO, spars and semi-submersible has a rigid mass equals to the mass it displaces in a surrounding sea medium. Tension Leg Platform is a sample of positively buoyant floating structures that has restraining system like tethered tank and anchor to seabed. The characteristic of floating structures make it considerably practical to be installed in deeper water compared to fixed jacket, gravity based structure or guyed tower in terms of technical and economic point of view. The floating production system is expected to blossom in the next decade and beyond.

1.1.2 Floating Production Storage Offloading Unit (FPSO)

FPSO is the production facilities that can stores the crude oil and locate it in the hull of vessel before offloads to tandem ship periodically. FPSO are permanently moored to a fully weathervane turret. FPSO is one of the floating structures units that are neutrally buoyant with dynamically unrestrained for the structure to move (Chakrabarti, 2005 pp.27).According to William, L., (2003), the first FPSO from the tanker conversion was installed in Mediterranean Sea, 1977. Predominately, FPSO have been used in North Sea, Brazil, Southeast Asian/South China Seas and off the West Coast of Africa. About thirty years from it first appearance, FPSO is dominating the offshore industry due to its simplicity and shows no sign of diminishing. Malaysia's first deep water FPSO was moored at Kikeh, Sabah with a water depth of 1330m and has one of the largest external turrets for FPSO worldwide. FPSO has no limitation on water depth and can be used in shallow or deep water exploration. The flexibility, reliability and the economically wise to be installed in any water depth had possessed the study for FPSO on hydrodynamic analysis due to environmental load such as wave, current and wind for excellent exploration and production especially in the deep water region.

1.2 PROBLEM STATEMENT

As the exploration of hydrocarbon started to reach the deeper water level, the analysis, design and construction of the floating offshore structures is arguably one of the most difficult works to be done. (Haritos, N., 2007). The offshore structures have the extra complication as in an ocean environment; the hydrodynamic responses and dynamic analysis of the wave forces are require in the structural design. So it is important to study the dynamic responses and provides useful information on hydrodynamic analysis for the preliminary design of the FPSO. The optimum design with suitable dimension can be located and operated at that specify environmental condition. The consultations on the hydrodynamic research and advice from the expertise on deepwater study are highly expensive for the Oil and Gas Company in Malaysia. Therefore, by completing this project, better understanding on FPSO responses subjected to regular and random waves can be fully utilized in offshore industry. Besides, the reliability of FPSO responses also can ensure the operation is safe and can sustain longer serviceability associated to the severe environmental condition with maximum production. The information gained from this research will also initiate further studies on the dynamic analysis of FPSO and will encourage the rapid progress of the deepwater development in Malaysia.

1.3 OBJECTIVES

The objectives that aimed to be achieved and to be completed by the end of this project are as follows:

1) To prepare a good detailed of literature survey on the motion response of FPSO.
2) To select the FPSO dimensions and all required data of typical FPSO for this project.
3) To complete a dynamic analysis of this typical FPSO due to a regular and random wave using (P-M Wave Spectrum) and to determine the motion responses of the FPSO in surge, heave and pitch direction.

1.4 SCOPE OF STUDY

In order to fulfill the objectives stated above, a further research and analysis need to be done within the time frame. The focus on this project is mainly related to the Offshore Engineering field which technically covered the hydrodynamics study for the floating structure. The small amplitude wave theory or known as Linear Airy Wave Theory was used to understand the fundamental concept of the water motion. The wave forces were calculated using Froude-Krylov equation and the calculation analysis has been performed in Microsoft Excel. In addition to that, the vessel motion responses; Response Amplitude Operators (RAO) due to wave forces was obtained in each surge, heave and pitch. Then, simulation of wave motion profile was generated from the P-M wave spectrum in random wave condition. Frequency domain analytical model was used to predict the responses of an FPSO because it much simpler, straightforward and employed linear prediction for more accurate results. Detailed environmental data and design was adapted from FPSO Ruby II project for a typical FPSO.

CHAPTER 2

LITERATURE REVIEW AND THEORIES

2.1 GENERAL

Many literatures were found on hydrodynamic analysis of FPSO due to the wave forces and the studied had been developed and introduced by conducted the experiments in wave basin and computed the numerical calculation (Xin Li et al., 2003; Ward et al., 2004; Zang et al.). Numerous studied on the motion responses in regular and random wave also been done and the analysis was carried out either in frequency domain, time domain or both approach (Yadav et al.,2007; Kim ,2004 & Sheming et al.,2002). Several number of literatures also been discussed on the coupling effect of mooring line and attached turret to FPSO responses, (Low, Y.M., & Langley, R.S., 2007; Kannah, T.R., & Natarajan, R., 2006). Most of the random wave's analysis in previous studies was governed by P-M wave spectrum model.

2.2 WAVE KINEMATICS AND WAVE FORCES THEORIES

Hydrodynamic is the physic of how the floating or fixed structures in sea water respond to the dynamic wave forces. This dynamic analysis gives useful information for the design of the FPSO. Too much motion will endangers the operation and become costly.

Haritos, N., (2007) give a comprehensive topics covered range of the water wave theories, structure-fluid interaction of waves to the prediction of extreme responses from the spectral modeling approaches. The approach analysis in this study proved to be quite satisfactory on the hydrodynamic loading effects, character of the dynamic responses and hydrodynamic loading characteristics of the structure-fluid interaction. The topic range covered the rigid structure and solid explanations on fundamental concept of Airy wave theory.

Wave theories describe the kinematics of waves on surface elevation. Linear Airy Wave Theory is the simplest and most applicable of all small amplitude wave theories. Wave theory can calculate the particle displacements, velocities, acceleration and dynamic pressure corresponds to wave elevation on the water surface. It is assumed that the waves in two dimensional X-Y plane with amplitude of *a*, at any instance of time of time *t* with depth, *d* and the waves are progressive in horizontal X-direction (Haritos, N., 2007 & Chakrabarti, 2001 p. 48). Generally, wave train is denoted by:

$$\eta\ (x,t) = a \cos\ (kx\text{-}\omega t) \tag{1}$$

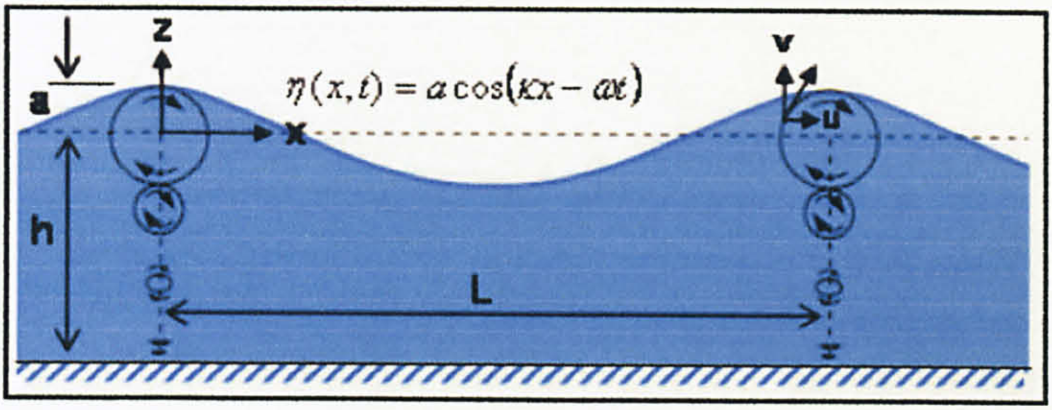

Figure 2.1: Definition Diagram for Airy Wave Theory

Wave is one of a significance environmental factor to be considered because it caused major impact to the motion of floating structure like FPSO. Wave is generated by the movement of the winds that blow to the sea water and grow into bigger waves and disappear after the wind ceases (Chakrabarti, 2001 p.86). Wave brings some forces when it smashes to the offshore structural and these forces can be calculated base on three conditions:

a) Morison's Equation – Wave forces on vertical tubular diameter cylinder. Sum of the inertia force proportional to the particle acceleration and a non-linear drag force proportional to the square of the particle velocity. Morison equation wills use together with Cm and Cd that depends on the size and the added mass of the cylinder in the water to obtain particle velocities and accelerations of the wave.

b) Diffraction theory – Large volume bodies compared to the wave length, caused Morison's equation no more applicable. Hydrodynamic compact structures influence and alter the wave field by diffraction and reflection upon arriving at the structure.

c) Froude-Krylov theory- Applicable when the drag force is small and inertia force predominates. It utilizes the incident wave pressure and the pressure-area method on the surface to compute the forces in its six-degree of motion.

2.3 STUDIES ON MOTION RESPONSES

Xin Li et al. (2003) have elaborated that as the water depth decrease, the wave frequency motions of the FPSO also decrease. Since the tested model and the numerical calculation of the data were in good agreement, the motion performance of large FPSO in shallow water can be predicted.

Successfully lab researched has been done by Ward et al. (2004) to investigate the behavior of generic tanker-based FPSOs in wave, wind, and currents conditions during severe Hurricanes in Gulf of Mexico. The model tests were conducted to examine the effect of FPSO to non-parallel waves, wind and current conditions and wave directionality. The results showed that the transverse responses particularly roll, has the influenced by non-parallel environments and directional seas. Important point has been highlighted from the experimental study represent that the measured responses in parallel wind, wave and current environments are not always larger than responses in non-parallel condition, which is the typical condition in hurricanes .Thus, simplified design methods

Comprehensive simulation on the global motion of FPSO due to vessel–mooring-riser coupled dynamic analysis has been developed in time-domain and studied has successfully done by Kim (2004). The vessel and line dynamics were solved simultaneously in a combined matrix for the given environmental and boundary conditions and the results were compared with FPSO model-testing with truncated mooring system. It is found that expected damping come from the long slender mooring line will reacts with total system stiffness and inertia. The study showed that, the dynamic mooring tension can be underestimated with truncated mooring system with significant effect of mooring motion. They also found that additional of risers and riser truncation caused more dynamic responses to the vessel.

In other studies, Sheming et al.(2002) had investigated the combining results of hydrostatic restoring force and moment in heave and pitch motions leads to excessive resonant rolling problems at different headings and frequencies. By using time-domain simulations, they found that the coupled heave and pitch motion with roll were bias due to pitch movements. So it was concluded that the instability of extra roll motion happened and when the vessel move in quartering waves at very low frequency.

In a well-documented literature by Low, Y.M., & Langley, R.S., (2007), the report clearly state that dynamic analysis of deepwater floating structure are complicated due to coupling dynamic of the FPSO with the attached riser and mooring lines. These significant nonlinear effects cause the equation of motion to be solved in time series. Though the mooring system is to provide the restoring force to the vessel, the action of the mooring system cannot be approximate as simple quasi –static spring because inertia and damping force increased from the mooring line may be comparable to the force acting directly to the vessel. From the research, time domain is efficient method to determine the inertia and damping contributions from the line in the form of non-linear coefficients. The result indicates the effect of mooring lines on the vessel damping will be large especially during the severe storm. The above factor must be considered if the mooring line and turret are been incorporate in this project.

based on parallel wind, wave and currents can unpredicted certain FPSO motion responses that important in preliminary design of FPSO in Gulf of Mexico.

Zang et al. was examined the effects of directional wave spreading on the non-linear hydrodynamic loads and the wave run-up around the bow of a floating vessel in random seas under uni-directional wave. The quadratic boundary element method has been used to solve linear wave scattering problem. In this study, excellent result has shown the interaction of radiated waves scattered and produced great elevations on the surface close to the body when big incoming wave crest impact the structural.

Detail studied has been done by Newman (2005) to analyze the hydrodynamic analysis of very large floating structures using radiation-diffraction code. The linear potential theory were used to see the wave effects on large offshore structures .Amplitudes of the incident waves, and unsteady motions of the structure are considered small compared to larger scales of the structures. First-order RAO and second order mean drift forces has been generated to analyze the effects of hydro elastic deformations, multiple bodies, and air cushion of the floating structure in time domain. However, the relationship between the relevant length for very large floating structures scales of hydrodynamic and structural gradient was not well discussed in this report

Yadav et al.(2007) studied the yaw instability of weathervaning FPSO subjected to different sea states. The parametric studies were performed for hull length and turret position and its effect instability of yaw in regular wave. Time domain simulations were conducted to verify the frequency domain analyses that indicate yaw responses was non-linear in nature as yaw increase when wave steepness increase. It was concluded that yaw is more influence by ship length to wavelength ratio than the natural period in roll. Internal turret influence more to instability of yaw compared to bow turret. As the turret position drawn closer to the mid-ship, there is increase in equilibrium yaw angle of FPSO.

Investigation done by Kannah, T.R., & Natarajan, R., (2006) show the comparison on the dynamic response for typical FPSO that moored externally with a fixed structure and by a vertical anchor leg mooring arrangement. The experiment was conducted for two types of mooring arrangements under regular wave under three conditions, 40, 70 and 100% of DWT with three respective hawser lengths, 15, 20 and 25 % of the FPSO length. Some important finding was obtained from the investigation and has been well discussed as follow; the hawser line forces are minimum at all operating condition for both type of mooring system. Second, for both types of moorings, the surge RAO has an increasing trend with the increase in DWT as well as the increase of wave height over wave length. The report was concluded that for a safe and good working environment of a FPSO system, the wave height over wave length of 0.20 is the best hawser-length –to ship-length ratio for less dynamic response for all both conditions. However the result obtained from this investigation may not applicable for a FPSO in deep water since results acquired were correspond to longer wave periods and have finite depth effect.

Apart from the literatures explained above, there were many more studied on the hydrodynamic analysis to the FPSO. Information on the coupled dynamic analysis on moored-turret FPSO and simulation in time-domain had provided extra knowledge on how FPSO responses were been analyzed in the real ocean environment. These literatures are helping the author to understand the dynamic responses of the typical FPSO due to the excitation of wave force at regular and random wave's condition.

CHAPTER 3

METHODOLOGY

3.1 WORK SCHEDULE

A gantt chart depicts the project progress in relation of time, and often used in planning and tracking the project. Gantt chart was developed in the early stage of the project and keeps the work progress in timely frame. This project was managed to complete within the planned schedule. Refer APPENDIX A for project milestone.

3.2 DESIGN BASIS AND ENVIRONMENTAL CRITERIA

3.2.1 Coordinate Axis

The FPSO global coordinate system (x,y,z) was applied to calculate the wave forces and moment as shows in Figure 3.1 . The origin (0,0,0) of the vessel was took at the intersection of centerline for longitudinal and transverse axis. The X-axis (longitudinal) is from the Aft - Bow side with positive direction to the Bow. The Y-axis (transverse) is from Starboard to Port with positive direction to the Port while Z-axis is on upward position of the vessel.

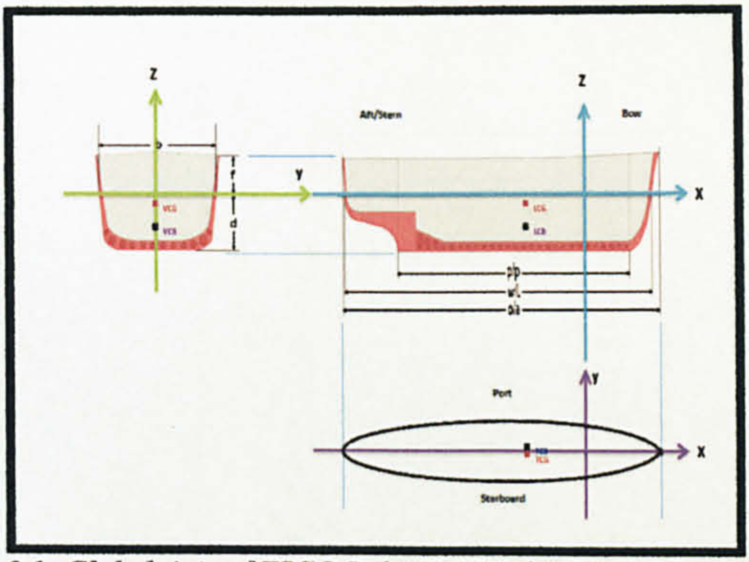

Figure 3.1: Global Axis of FPSO Ruby II (Weight Control Report, 2008)

3.2.2 Structural Dimension

The technical data was obtained from the FPSO Ruby II Project. The data was extracted from Pearl Development Project Block 01 & 02, Offshore Vietnam. Based on the raw data provided in the FPSO Ruby II project, the author needs to approximate the basic and conservative dimension of the vessel that been used at 1200m water depth. This water depth was assumed in the calculation since the main interest of this project is to explore the wave forces impact to the floating structure in the deep water area. The mooring and offloading system attach to the FPSO were excluded in the calculation of wave force because that needs a complex methodology approach. Figures 3.2, 3.3 & 3.4 show illustrated dimension of FPSO:

Table 3.1: FPSO Dimensions

Specifications	Design Scale
Length overall LOA(m)	275
Length Between Perpendiculars LBP (m)	250
Breadth(m)	45
Depth (m)	24
Design Draft (m)	18
Weight (M-Kg)	216

The general arrangements of the vessel after some modification from the original dimension of FPSO Ruby II is shows as below: All layouts were made by using the *Autocad 2007* software.

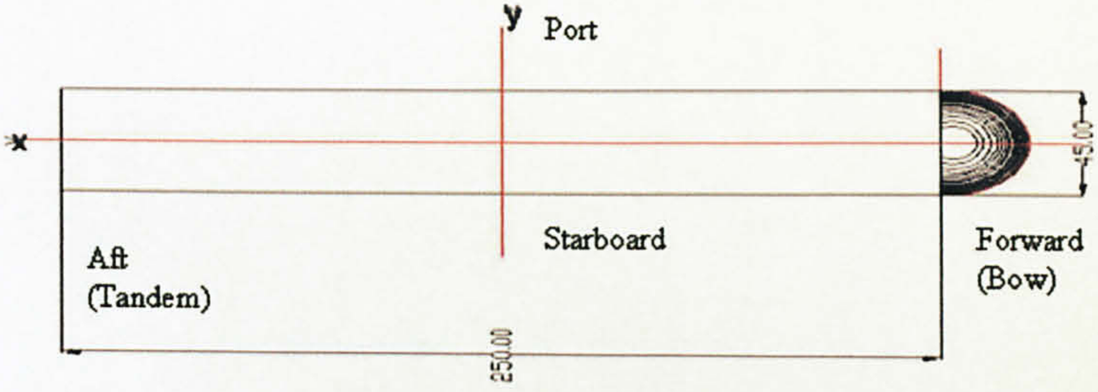

Figure 3.2: Plan-View Design of FPSO

Basically the vessel was divided into two main parts; first part is a rectangular shape hull and assumed to be loaded with standard facilities on topside and has the cross sectional area of 6m x 45m from the top MSL and the second part is a horizontal half cylinder with the 18m of draft to the bottom keel of the FPSO. The semi-elliptical shape of bow was selected and used in this project because this shape is most representing the normal shape of the conventional design of FPSO. Refer Figure 3.2 for the plan-view of the FPSO.

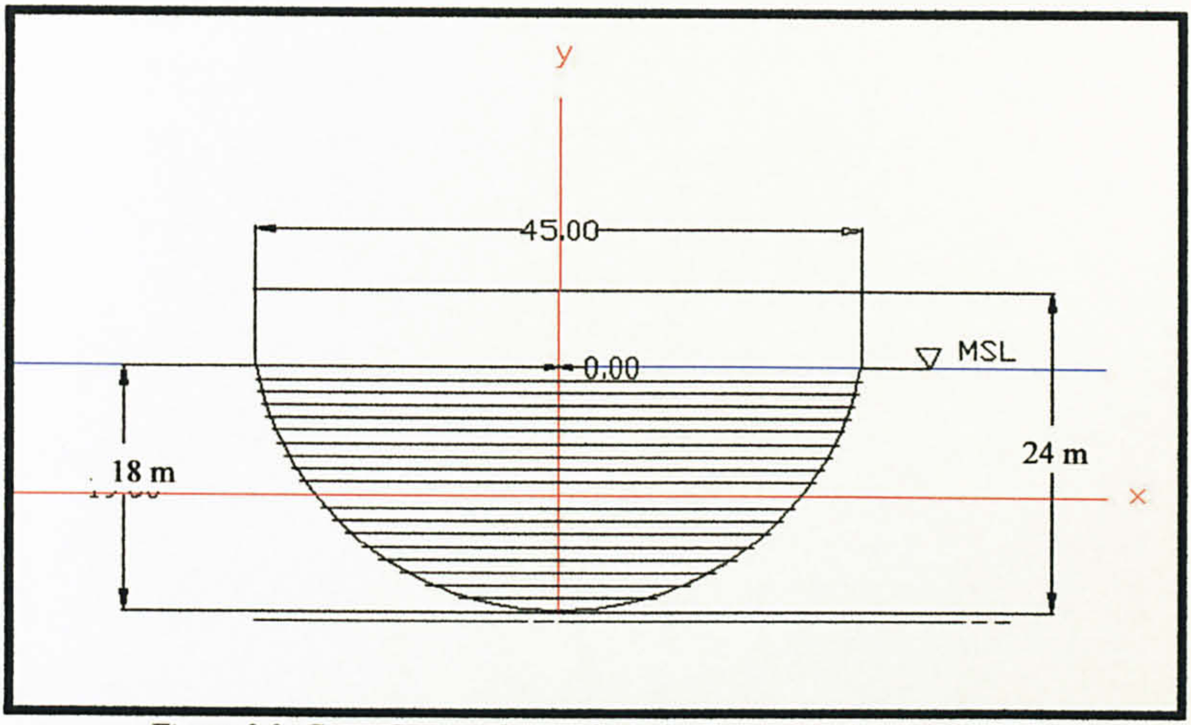

Figure 3.3: Cross-Sectional Area from the Bow and Aft Side of FPSO

The cross-sectional areas of the vessel were assumed to be same at the aft and the bow side. Figure 3.3 show the cross-sectional area of the draft that has been equally distributed into 1m depth and each layer consists of difference value of cross-sectional area as reported in **APPENDIX B.** The area was calculated by using the basic semi-elliptical area equation. A = Παb.

The surface area on bottom side of the vessel was used to calculate the vertical wave forces on y-axis component. Figure 3.4 shows the design shape of half -cylindrical hull for FPSO.

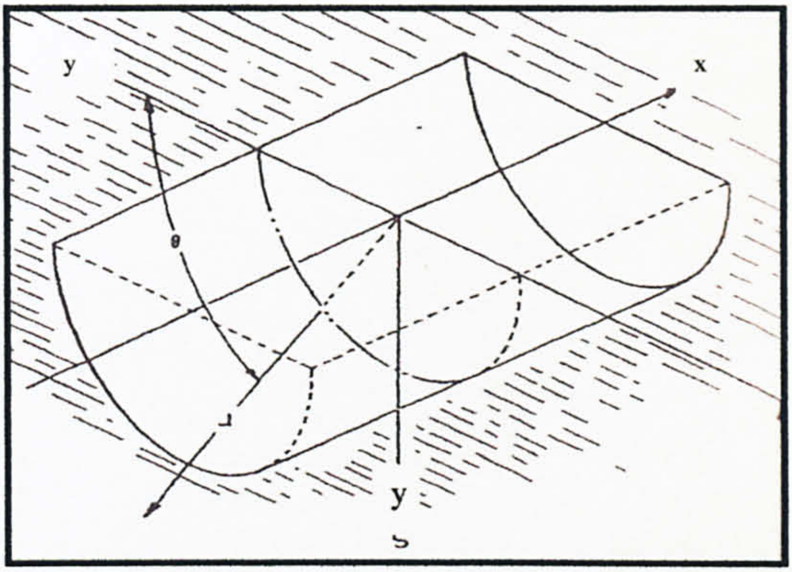

Figure 3.4: Half-Cylinder Shape at the Bottom Side

3.2.3 Environmental Design Conditions

The environmental criteria consist of wave height, period, wind and current speed for both operating and storm condition with design basis of 1 year or 100 years of return period. For a experimenting and analysis purposes, a 1-year non-typhoon event was considered as the survival environmental conditions in this project. The operating conditions set for a vessel indicate that the vessel must be able to produce oil and offload about ninety-five percent of the years and stay linked to the moorings and riser systems under a one year of non-typhoon storm event (Curt et al., 2006). The environmental data for 1 year operating condition was obtained from Provision of FPSO/FSO Feasibility Study: Design Basis Report (Doc.No.4009-MISC-81-FS (DG)-002.Rev.C) where the details are as follows:

Table 3.2: Environmental Data at 1 Year Operating Condition

Environmental Condition	Parametric
Maximum Wave Height (Hmax)	9.6m
Significant Wave Height (Hs)	4.9m
Significant Peak Wave Period (Tp)	9.6sec
Significant Zero Crossing Period (Tz)	6.8sec
Associated Zero Wave Period (Tass)	8.9sec

3.3 THEORETICAL CALCULATION

3.3.1 Wave Forces and Moment Calculation

Since FPSO is a big structural and have larger surface area, Froude-Krylov theory is the most applicable method for calculating the wave forces in this project. As mentioned in (Chakrabati, 2001, p.331), Froude-Krylov equation is the diffraction force on the structure at its equilibrium condition and the radiation forces on the structure in its six degree of displacements, refer to Figure 3.5.

Originally from the Froude Krylov theory, the total forces on the structure can be determined by integrating the pressure component whether in horizontal or vertical direction over the submerged portion of the vessel. The expressions for the horizontal and vertical force components in the *x* and *y* directions are as follows:

$$F_x = C_H \iint p n_x dS \tag{2}$$

and

$$F_y = C_H \iint p n_y dS \tag{3}$$

The recommended horizontal and vertical force coefficients, Ch and Cv for the submerged structures are included in **APPENDIX C.**

n_x and n_y = directional normal to horizontal and vertical

dS = an elemental area of submerged surface of the structure

However in this project, the above equation has been simplified by using the fundamental equation of the force, to suit the conservative dimension of FPSO designed for this project.

Horizontal Force, $Fx = P \times A \times Ch$ (4)

Vertical Force, $Fy = P \times A \times Cv$ (5)

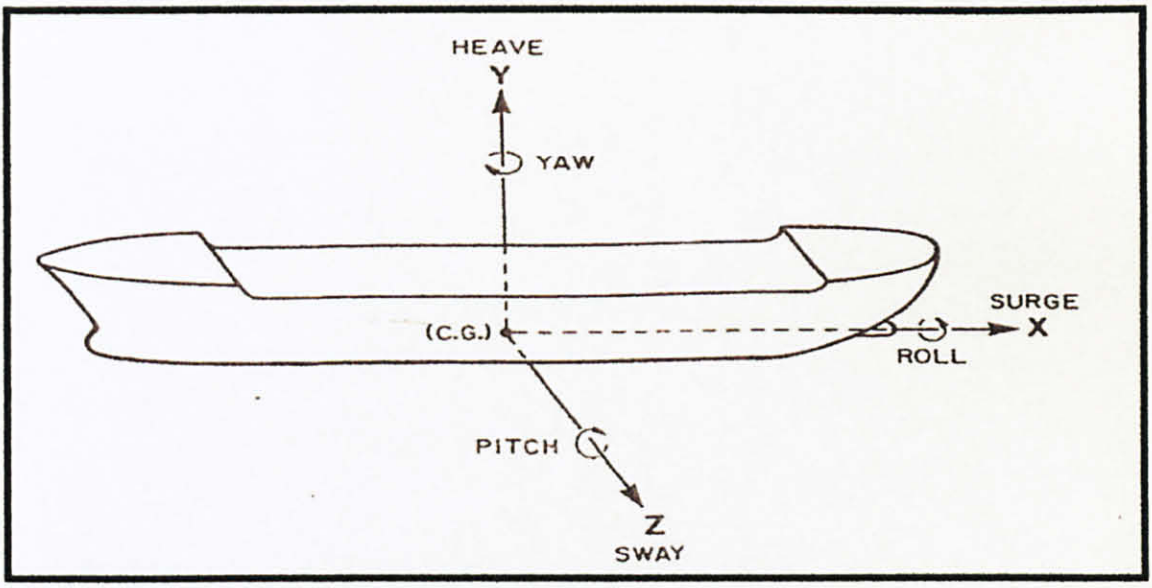

Figure 3.5: Definition of Six Degrees of Motion of A Floating Tanker (Chakrabati, 2001)

The expression of ρ, represents the dynamic pressure from the Linear Airy Wave Theory or known as sinusoidal wave theory. It was derived based on assumption that the wave height is small compared to the wave length or water depth. The pressure is assumed to act normal to the submerged structure surface at the particular point at particular surface area. Theoretically, ρ is given as;

Dynamic Pressure, (6)

$$\rho = \rho g \frac{H}{2} \frac{\cosh ks}{\cosh kd} \cos (kx - \omega t) \qquad (6)$$

Where,

ρ ,density = 1025 kg /m^3 ; g = 9.807m/s^2

H = Maximum Wave Height (m)

T = Associated wave period

$s = y + d$, elevation from seabed; y, height of the point of evaluation of water particle kinematics; d, water depth

Θ = kx-ωt; k, wave number = 2Π/L (rad/m); x, point at origin; ω, natural frequency 2Π/T (rad/s); t, time instant at which particle kinematics is evaluated (s)

The main six degree of motion consist of three translational (surge, heave, sway) and three rotational (roll, yaw, pitch) but in this project, the FPSO was modeled as a floating body with three degrees-of –freedom; surge, heave and pitch because waves was assumed to propagate in uni-directional wave.

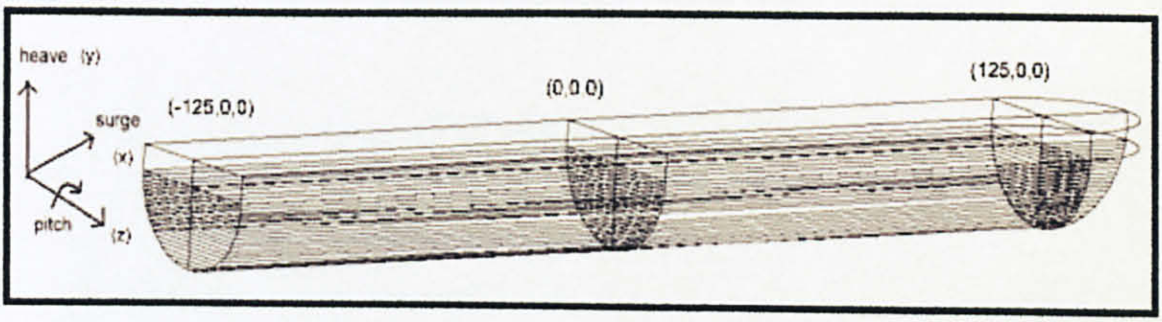

Figure 3.6: FPSO Layout

The maximum wave forces were calculated for surge (Fx) and heave (Fy) of the FPSO direction. For surge motion-direction, summation of forces was taken from Aft and Bow (Fx-component) side. While in heave, forces were calculated by adding the forces from the Bottom of FPSO and Bow Side (Fy-component). Forces that acting below the draft was calculated for t=0s until t=9s for both surge and heave. Then, the maximum wave forces for each period, t were selected to generate response amplitude by using equation (7). After the wave forces acting at the X and Y direction were secured, moment was calculated with respect to the COG, center of gravity of FPSO Ruby II. Moment value was used to determine the pitch responses. The center of gravity data was obtained from the Weight Control Report for FPSO Ruby II.

3.3.2 Frequency Domain Analysis

The theoretical study was carried out for both regular and random wave conditions. Practically, the motion of heave, surge and pitch was calculated in frequency domain. Then the energy density distribution was analyzed from the motion-response spectrum and the motion response profile was extracted from this motion-response spectrum.

3.3.3 Motion Responses

Response Amplitude Operator was used as wave amplitude factor to determine the responses at each motion-direction (i.e surge, heave and pitch motion) when subjected to random wave. The RAO equation of motion can be written as;

RAO Equation,

$$\left| \frac{F_i / [(Hmax)/2]}{[(K-m\omega^2)^2+(C\omega)^2]^{1/2}} \right| \tag{7}$$

Where,

F_I = Maximum force of Fx or Fy

$C = \omega n * m * \zeta$, with damping ratio of ζ= 5%

ω^2 = K/m,

$\omega n = 2\,\Pi / Tn$; Tn is natural period

K = stiffness of the structure

m = actual mass + added mass

3.3.4 P-M Wave Spectrum

The energy spectrum distribution for each of the motion was calculated using the PM-Wave Spectrum in range of (0,2Π) .Microsoft Excel was used to compute all the data and graphs in this project. From (Chakrabati, 2001);

The P-M spectrum model is defined as:

$$S(f) = \frac{\alpha g^2}{(2\Pi)^4} [f^{-5}\exp[-1.25(f/f_0)^4] \qquad (8)$$

Where $\alpha = 0.081$

The relationship between peak frequency, $f_o = \omega_o/2\Pi$ to the significant wave height, Hs is obtained as follows:

$$\omega^2_o = 0.161g/Hs \qquad (9)$$

In random wave, the bell-shaped of the spectrum graph was divided into several equal band width of frequency and each frequency fx has its own motion-response spectrum $S_x(f)$ with respective wave height of H (fi) as follows:

$$H(f_1) = 2\sqrt{2(f_1)\Delta f} \qquad (10)$$

This relationship was transformed to evaluate the motion spectrum in terms of wave spectrum and RAO. The equation was obtained by multiplied the equation (8) with square of RAO from surge, heave and pitch direction. The equation can be expressed as follows:

$$S_x(f) = \left| \frac{F_i/[(Hmax)/2]}{[(K-m\omega^2)^2+(C\omega)^2]^{1/2}} \right|^2 s(f) \qquad (11)$$

3.3.5 Wave Profile from Spectra

From the resulting motion-response spectrum obtained from equation (11) for a given coordinate x, which location of wave profile needed, the motion-response profile for random wave in each degree of freedom was obtained by using the equation below:

$$\eta(x,t) = \sum_{n=1}^{N} \frac{H(n)}{2} \cos\left[k(n)x - 2\pi f(n)t + \varepsilon(n)\right] \quad (12)$$

Where,

- Time, t which is incremented varies from t=0s to t=500s
- k(n)= 2Π/L(n) ; L(n) correspond to the wave length for the nth frequency *f*(n)
- Δf, equal width frequency by dividing 2Π with 40 component for randomness
- ξ(n) is a random number generated in Microsoft excel.

CHAPTER 4

RESULT AND DISCUSSIONS

4.1 FPSO WEIGHT

From the Archimedes Principle, the wholly or partially submerged weight in the water that buoyed up the force equal to weight of water displacement by the vessel. Weight of the FPSO was obtained by calculating the volume of each component of the vessel. To ease the calculation, the FPSO draft was set into two parts; the half cylinder shape; representing the bottom side of the FPSO and the semi-elliptical shape at the bow side, as illustrated in Figure 3.6.Total volume for this FPSO **is 209, 407m^3** and the total FPSO weight is **216 M-kg.** Refer **APPENDIX D** for details of weight calculation.

4.2 MOTION RESPONSES

The motion responses for surge and heave and pitch were obtained from equation (7) with 5% damping ratio under the condition of regular waves. The maximum amplitude for the surge, heave and pitch motion response at x=0m, x=125m and x=-125m was summarized in Table 4.1. Since the result obtained for x=125m and x=-125m were same, only statistical graph at x=0m and x=125m will be discussed in this report to avoid redundancy. Refer **APPENDIX G** for the details calculation of motion-response of the FPSO in regular waves.

Table 4.1: Motion Responses on Surge, Heave and Pitch of Regular Waves

X- Location (m)	Surge (m)	Heave (m)	Pitch (radians)
0	0.2082	0.2470	0.00049
125	0.2077	0.2464	
-125	0.2077	0.2464	

The motion responses from the table 4.1 shows that the FPSO move a bit higher in heave direction about 0.25 m and about 0.21 m in surge direction. The vessel rotates about 0.00049 rad in pitch motion. The motion offset for both motion-directions are different due to several factors. Among the factors that can effect the dynamic response of the FPSO are i) Total force and moment, ii) added mass, iii) surface area of the vessel to the wave impact and iv) natural period and v) mooring lines and its stiffness.

4.2.1 Force and Moment Calculation

Froude Krylov Equation from equation (4) and (5) was used to calculate the wave forces acting to the submerged surface of the FPSO for surge and heave motion with respective to dynamic pressure in equation (6), multiplied with the cross-sectional area shows in **APPENDIX B** .

Wave forces in surge motion was calculated by sum up the forces from the Bow (Fx) and Aft side. Since the bow side of the FPSO has been designated with the semi-elliptical shape, the wave attacking normal to the structure was designed to attack the bow side in sequential angle of 0°, 15°, 30°, 45°, 60° ,75° and 90° degree, refer Figure 4.1. These wave-angle directions will generate the Fx and Fy component at the bow side. While the wave forces from aft side were assumed to act perpendicular to the flat surface of FPSO. The wave forces that attacking the side port and starboard were assumed to cancel each other since the FPSO is assumed to move in uni-directional in x-axis.

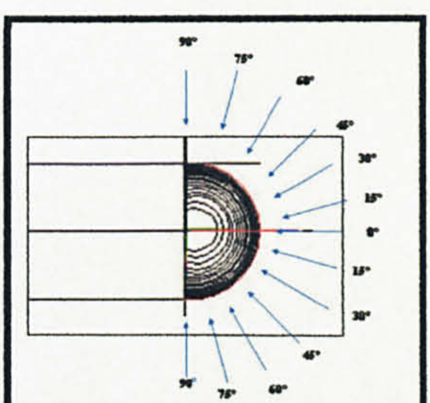

Figure 4.1: Waves Angle Direction at Bow Side

Meanwhile for the heave motion, the forces was calculate by sum up (Fy) component from bow side and vertical forces acting on the bottom side. As discussed in Chapter 3, the wave forces from the keel side of the vessel were assumed to attack the bottom of the FPSO with the same wave-angle directions shows in Figure 4.1.This is because the FPSO hull is design in curvature shapes- half cylindrical draft, so derivation of the wave-angle also needed same as the calculation of the forces in bow side. Refer **APPENDIX E** for detail calculation of the forces in surge and heave motion.

The center of gravity for FPSO Ruby II was taken from Weight Control Report for FPSO Ruby II and was assumed to operate with 100% full load condition. The locations of the COG are:

a) VCG = 14.15m above the keel
b) LCG = 139.81m forward of (facing to the stern)
c) TCG = 0.19m port of the centerline

The pitch movement was controlled by the wave forces from surge axis. Due to maximum wave forces in surge; large moment was induced in counter clockwise direction. Since the FPSO assumed to float upright in still water, the COB and the COG of the vessel will be in the same line above the keel. So the FPSO always in stable state and caused minimum rotation in pitch direction. Refer **APPENDIX F** for details of the moment calculation.

The maximum wave forces were calculated for the bow, aft, and bottom side of the FPSO and as summarizes in Table 4.2.

Table 4.2: Maximum Wave Forces on FPSO Ruby II

X- Location (m)	Surge, Fx (MN)	Heave, Fy (MN)	Pitch (MN-m)
0	108.04	75.99	302.10
125	107.77	75.80	301.34
-125	107.77	75.80	301.34

4.2.2 Added Mass

Added mass was applied to determine the inertia added when the body were forced to oscillate sinusoidal with small amplitude, for several submergences body below the sea water level and how much the water resists to the movement of the floating structure such as FPSO.The added mass is shown to be influenced strongly by the function of water depth, frequency and direction of wave oscillation. (Chung, J.S, 1994). The added mass for surge is 6.22 M-kg whilst for heave, 518 M-kg. However added mass in the heave direction was assumed to be same as FPSO buoyancy weight, 216M-kg because the whole volume under the draft was considered to have the additional effect (force) resulting from the fluid acting to the structure when the FPSO is in motion. Table 4.3 is the summary of total mass in surge and heave motion.

Table 4.3: Summary of Total Mass in Surge and Heave Motion

Location	FPSO Mass (M-kg)	Added Mass (M-kg)	Total Mass(M-kg)
Surge	216	6.22	222.2
Heave	216	216	432

4.2.3 Water Plane Area

Other factor that reflects the forces on heave and surge motion is a surface area of the FPSO. Surface area on the bottom side of FPSO was contributed in calculating the forces on heave motion. Water plane, the part of the hull intersected by the water's surface, is a primary determinant of motion. As the waves pass the hull, the buoyancy of the hull below the water remains the same. The larger water surface area indicate that the more sensitivity of the forces acting on the surface. The ease the calculation, the large surface of the FPSO area has been divided into small strip area as shows in Figure 4.2. The wave forces ($\sum Fy$) were calculated by taking the wave dynamic pressure that acting normal to this area. Against from the surge motion, only cross sectional area of the semi-elliptical shape at the bow and aft side was applied in calculating the surge force. Pitch motion are not been effected by the water plane area since pitch motion depends on the center gravity of the FPSO.

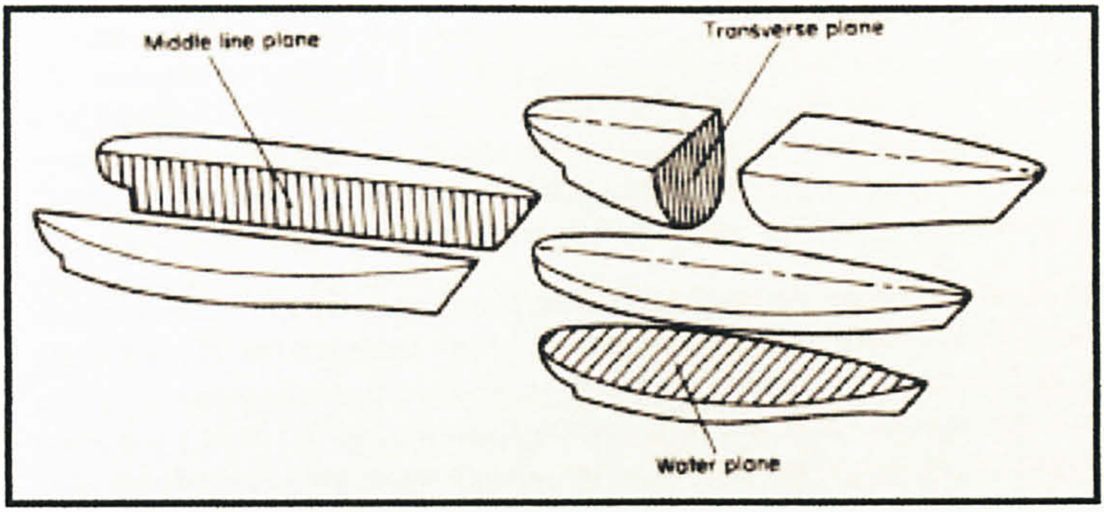

Figure 4.2: Water Plane Area

4.2.4 Natural Period

The relationship between the frequencies of the wave components and the natural period caused the motion response of the vessel. The natural periods was taken from Ward et al., (2004) as defines in Table 4.4.

Table 4.4: Natural Periods

Mode	Period (sec)
Surge	206.8
Heave	10.7
Pitch	10.5

From the motion result, heave responses are higher because of the higher dynamic amplification factor. This happens because frequency ratio; predominant frequency over natural frequency ($\omega/\omega n$) is almost equal to 1.0. This happened when the predominant period, taken for this FPSO was 9s and almost to natural period of heave, 10.7s. So the damping has a profound very large dynamics amplification and thus effect the deflection on the heave motion with damping ratio of 5%. The allowable maximum damping ratio that can be applied for offshore structures is 20%. Refer Figure 4.3 for dynamic amplification factor vs frequency ratio.

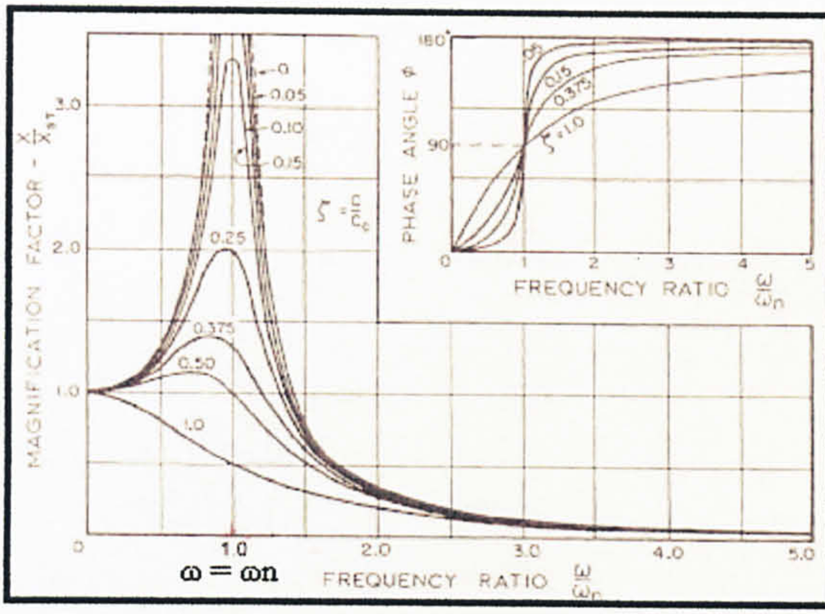

Figure 4.3: DAF vs Frequency ratio (Chakrabakti, 2001)

4.2.5 Mooring Line and Turret System

In the theoretical calculation for the forces, the mooring line and offloading system of the FPSO was not technically taken into calculation but the mooring line stiffness of the FPSO was obtained by reversed-engineering the equation ($K=m\omega^2_n$). FPSO is assumed to be rigid and the mooring line was considered as the stiffener to the structure, thus can hold and limit the FPSO motion especially in the vertical direction. Normally mooring lines were hinged to and spread from the turret. Table 4.5 shows that the larger stiffness will limit the motion of the structural because it can resist and hold the structural from moving. The turret type mooring systems also can help the vessels to weathervane, and minimize the force rely on the mooring lines system.

Table 4.5: Stiffness Value at Surge, Heave and Pitch Motion

Surge	0.2051M-N/m
Heave	148.96M-N/m
Pitch	336911.14 M-N/rad

4.3 WAVE SPECTRUM (P-M WAVE SPECTRUM)

S (*f*) from equation (8) will generate the energy wave spectrum with significance wave height of 4.9m. The frequencies range used were varies from 0 Hz – 0.4 Hz (0s-2.5s) with 40 components increment of 0.01 Hz. From the spectrum graph in Figure 4.4, the actual input wave energy spectrum was drew from 0.05 Hz to 0.35 Hz with maximum wave energy at frequency 0.095 Hz and about 23.238 m^2-sec of density energy spectrums. The value indicates the real condition of the wave energy at the sea state without existence of any floating structure. Refer **APPENDIX H** for details calculation for P-M Wave spectrum.

Time-history was stipulated from the equation (12) with the setting period from t=0s to t=500s. Statistical analysis in Figure 4.5 shows that maximum wave height is approximately at 2.65m.

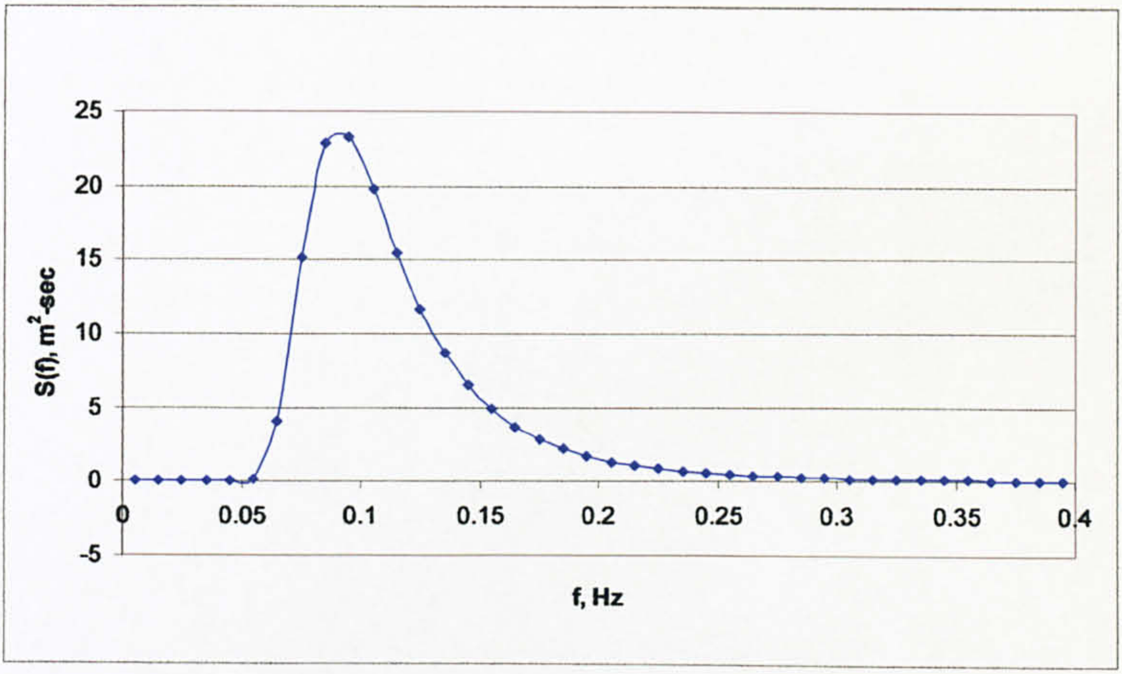

Figure 4.4: P-M Wave Spectrum for Hs = 4.9m

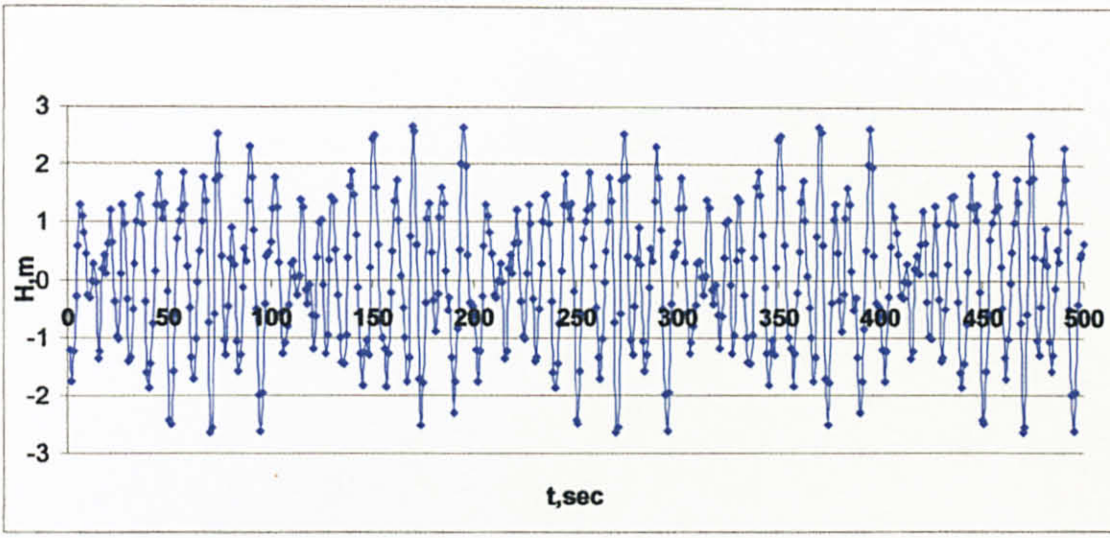

Figure 4.5: Simulated Time Series at x=0m (t=0s to t=500s)

4.4 MOTION- RESPONSE SPECTRUM

In ocean environment, the vessel motion is governed by the wave spectrum. As discussed in section 3.3.4, the motion responses spectrum for surge, heave and pitch of the FPSO motions was determined by using the equation (11).

The RAO vs frequency graphs at x=0m, x=125m and x=-125m for surge, heave and pitch motion were represented the motion responses of the FPSO due to the wave forces for each of respective frequency f_x. The respected graphs show in Figures 4.6, 4.9, 4.12. Then, Figures 4.7, 4.10 and 4.13 illustrates the RAOs from each frequency, $f_{x\ \mathrm{that}}$ has been multiplied with P-M model obtained from section 4.3 to get its own motion- responses spectrum S (f) $_{x}$,. The wave height from the motion responses can be observed in Figures 4.8, 4.11, 4.14. APPENDIX I show the summaries of RAO vs frequency for surge, heave and pitch motion.

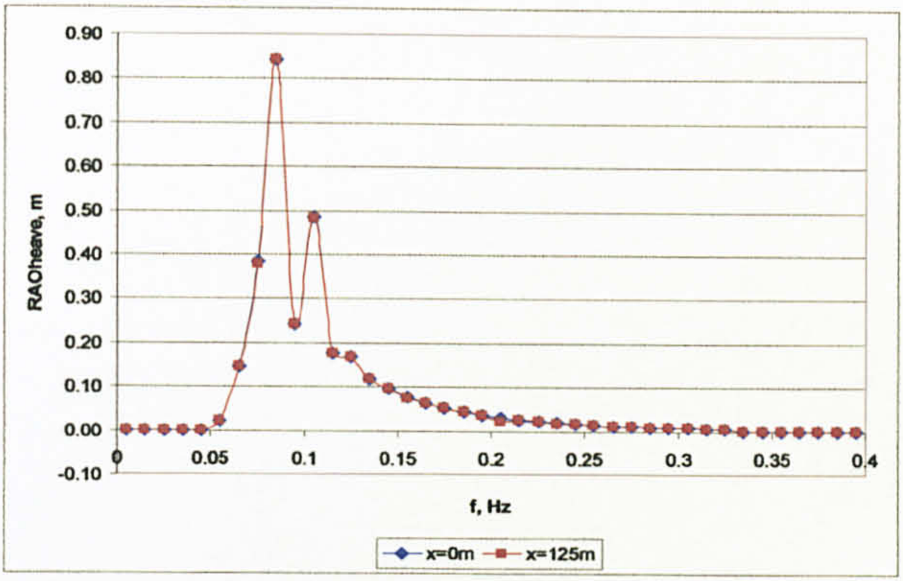

Figure 4.9: Motion Responses in Heave

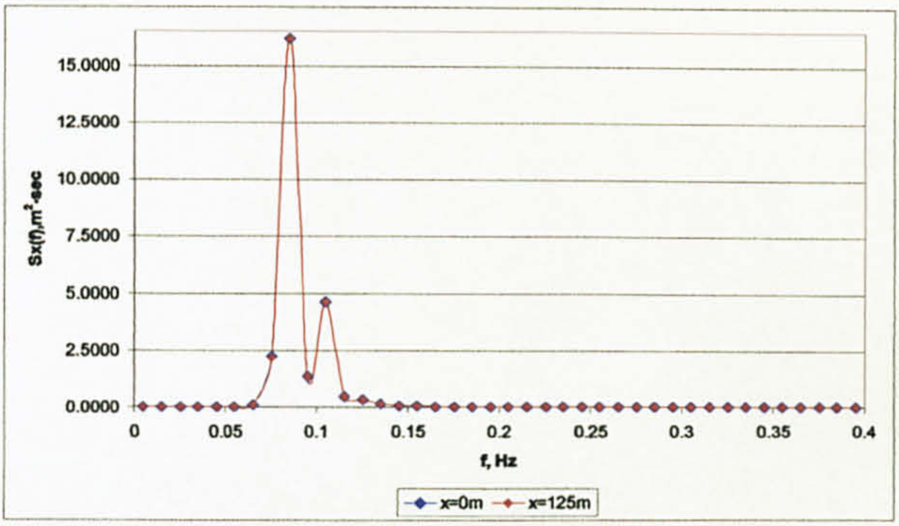

Figure 4.10: Heave Responses Spectrum

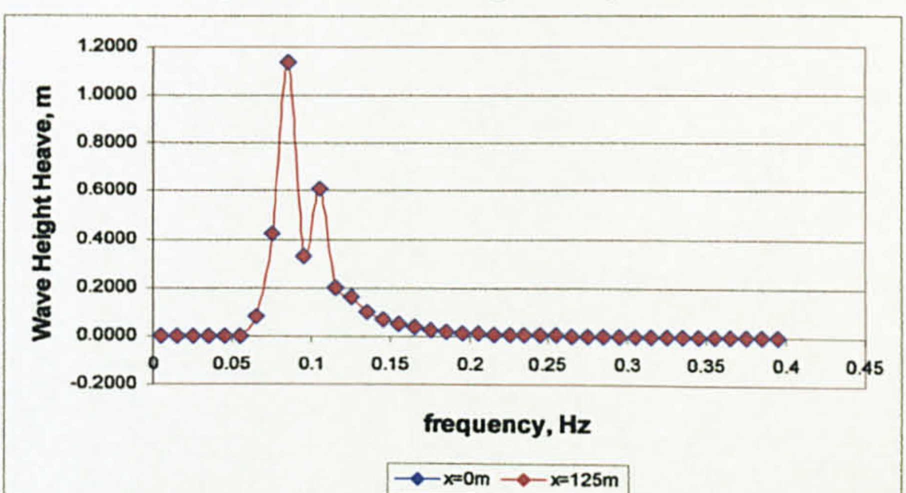

Figure 4.11: Heave Wave Height vs Frequency

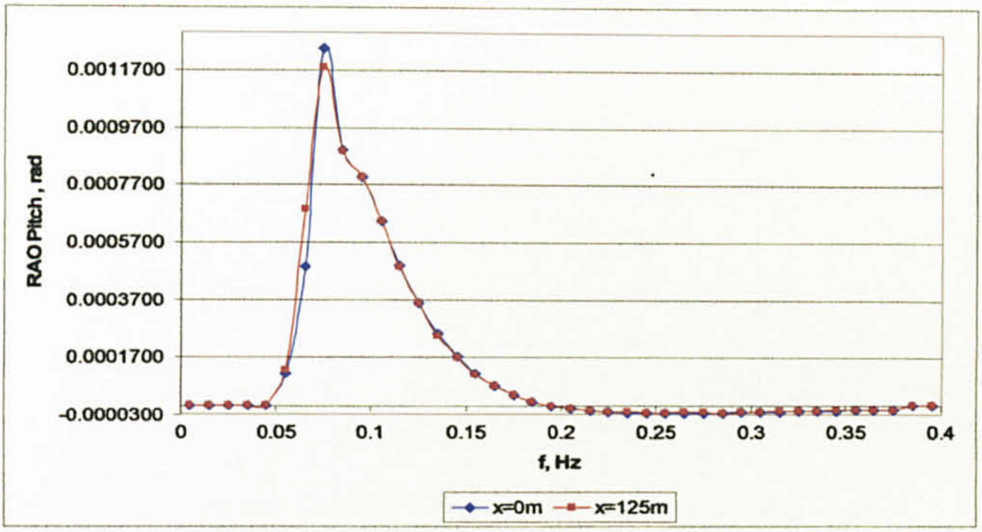

Figure 4.12: Motion Responses in Pitch

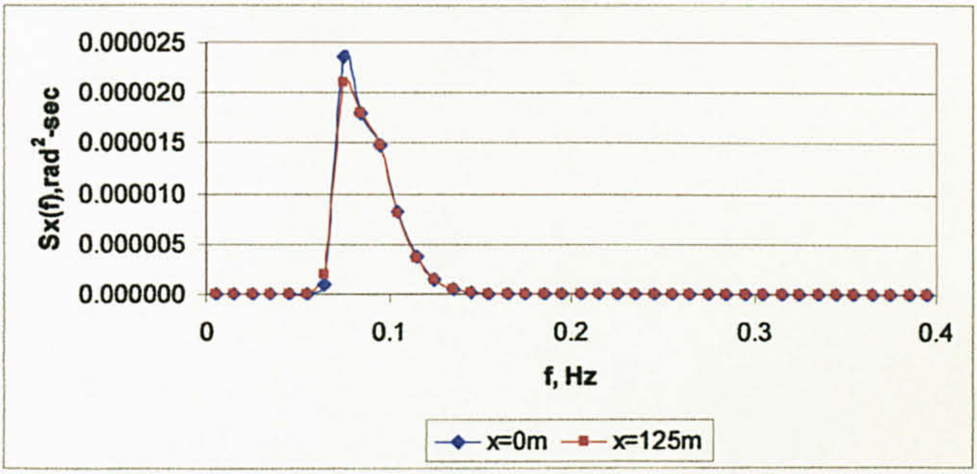

Figure 4.13: Pitch Responses Spectrum

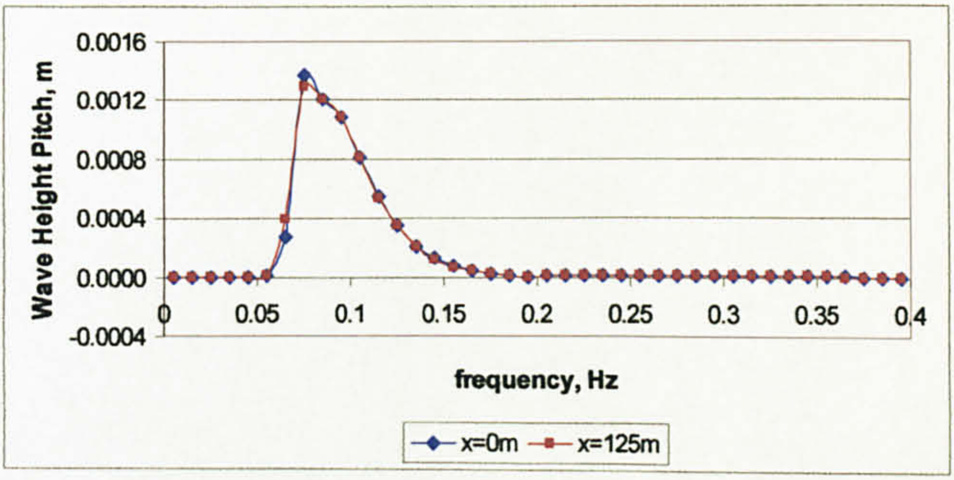

Figure 4.14: Pitch Wave Height vs Frequency

The motion responses spectrum graphs above indicate that in the real sea state situation, waves are moving randomly whether in surge heave or pitch motion. For surge and pitch motion, the range for the higher energy spectrum was drawn is range of 0.05 Hz to 0.15 Hz with the highest wave energy density at frequency 0.075 Hz. While for the heave motion, range for the spectrum was drawn up from 0.625 Hz to 0.125 Hz with maximum energy density at 0.095 Hz.

The energy spectrum density of the result at these three motions were observed and expected to be lower from the actual wave spectrum in section 4.3 because the behavior of waves that naturally will be disturbed if any structural exist at that location. Table 4.6 provides the maximum result at surge, heave and pitch motion at x=0m, since all the maximum value were remarked at location x=0m. The graphs above were obtained based on the methodology approach in section 3.3 and the differences values between these three motions are due to several factors that well discussed in section 4.1.

Table 4.6: Maximum result from Motion-Spectrum Response at x=0m

Maximum Result	Surge	Heave	Pitch
Frequency, f_x (Hz)	0.075	0.085	0.075
Energy Spectrum, $S_x(f)$	19.72 m^2-sec	16.17 m^2-sec	0.000024 rad^2-sec
Wave Height, H (m)	1.25	1.14	0.0014
Motion response, RAO	1.14 m	0.84m	0.00125rad

4.5 WAVE PROFILE

Equation (12) was used to calculate the time-history of the wave profile from the spectrums result obtained in section 4.3 at location x=0m, x=125m and x=-125m of the FPSO. These stipulated motion profiles strongly imply the structural responses due to wave forces within the time given (t = 0s to t =500s) in surge, heave and pitch. A random phase is in range (0,2Π) and random number was assigned to alter the randomness of the time history. The maximum amplitudes at location x=0m, x=125m and x =-125m of the three motion responses are recorded in Table 4.7.

Table 4.7: The maximum response –wave amplitude

Location	Surge (m)	Heave(m)	Pitch(rad)
x = 0m (mid ship)	1.37	0.93	0.00173
x = 125m (at bow side)	1.40	0.93	0.00179
x = -125m (at aft side)	1.40	0.93	0.00179

The specified wave profile is shows in Figures 4.15 & 4.16 for surge, Figures 4.17 & 4.18 for heave and Figures 4.19 & 4.20 for pitch.

The results obtained from this analysis indicate that:

a) Three differences coordinate were selected on the FPSO at mid ship (x=0m), at bow side (x=125m) and at aft side (x=-125m) just to denote any differences of wave impact to the FPSO motion due to different location. The results show that the motion responses at these three locations give only small differences and assume to be same since the concentrated load on the vessel is designed to be equally distributed on the FPSO.
b) Surge, heave and pitch motion-responses obtained from the result are acceptable and within the expected amplification factor.
c) The predicted responses only an approximation since frequency domain analysis used not covered the non-linearities like drag forces and mooring system.

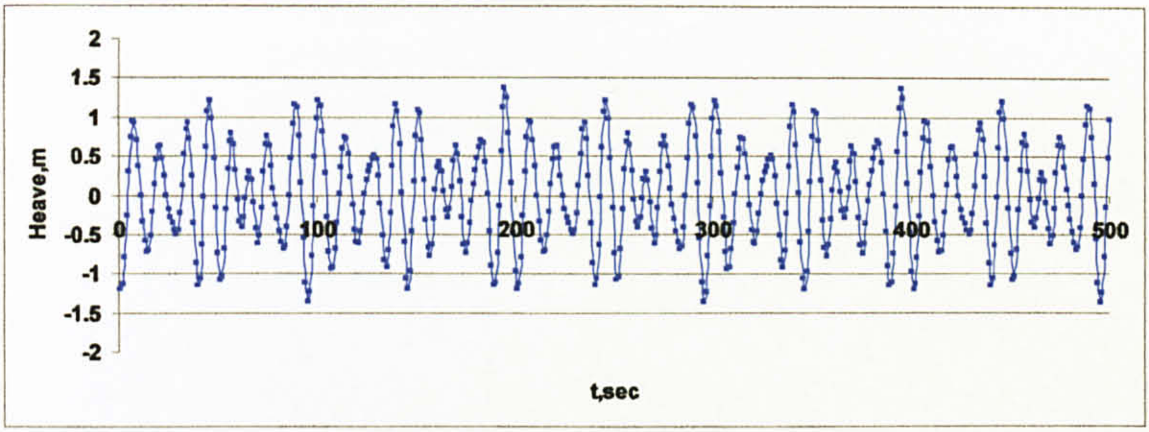

Figure 4.15: Surge Profile for Surge Response Spectrum at x=0m

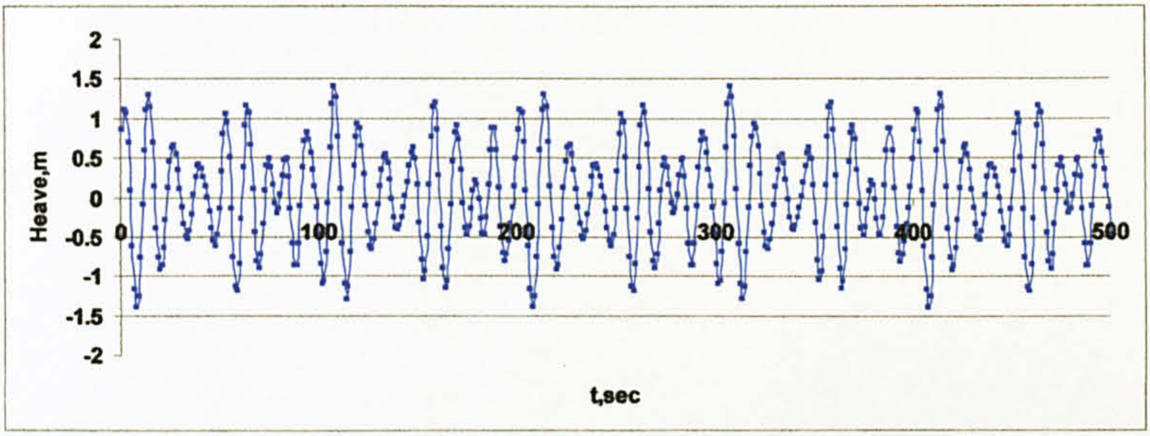

Figure 4.16: Surge Profile for Surge Response Spectrum at x=125m

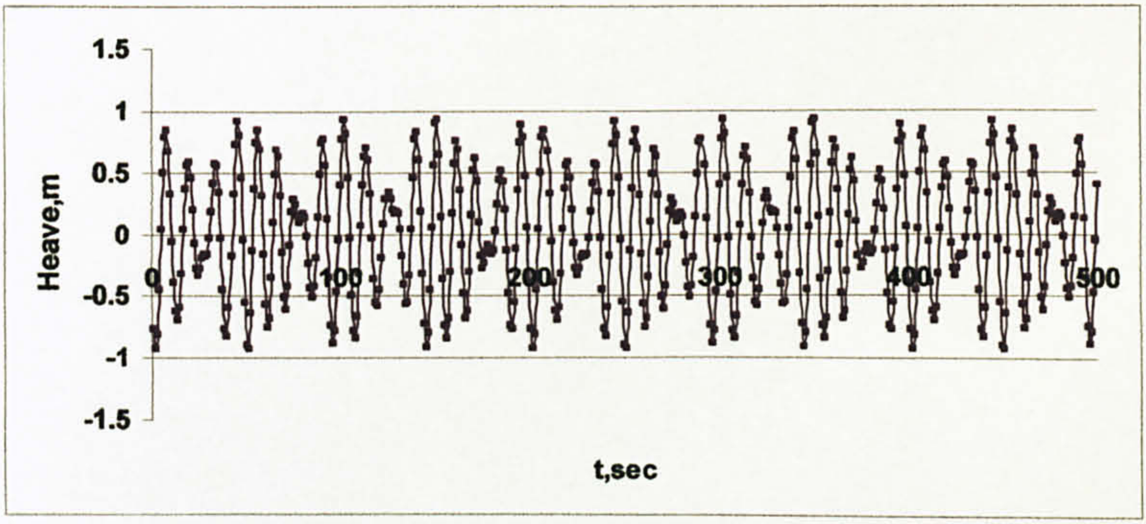

Figure 4.17: Heave Profile for Heave Response Spectrum at x=0m

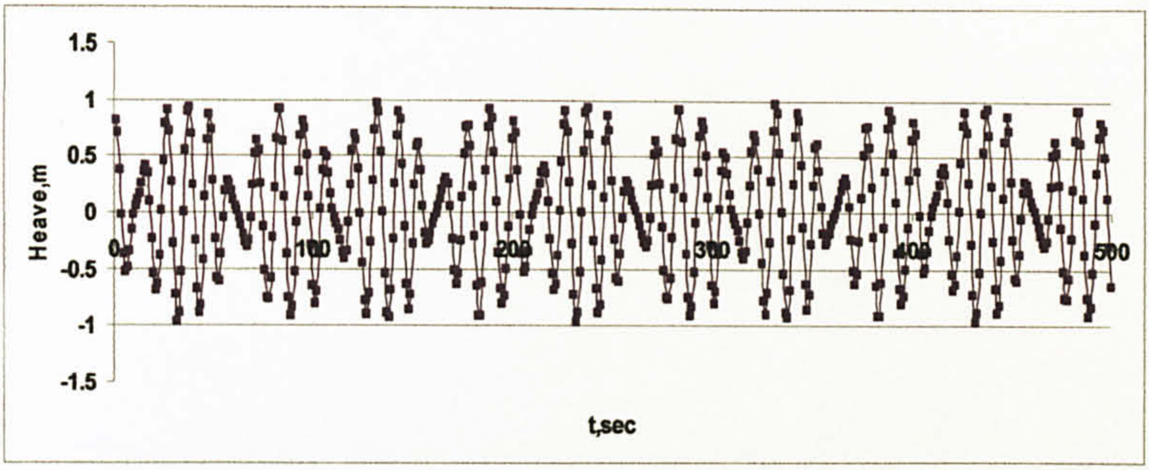

Figure 4.18: Heave Profile for heave Response Spectrum at x=125m

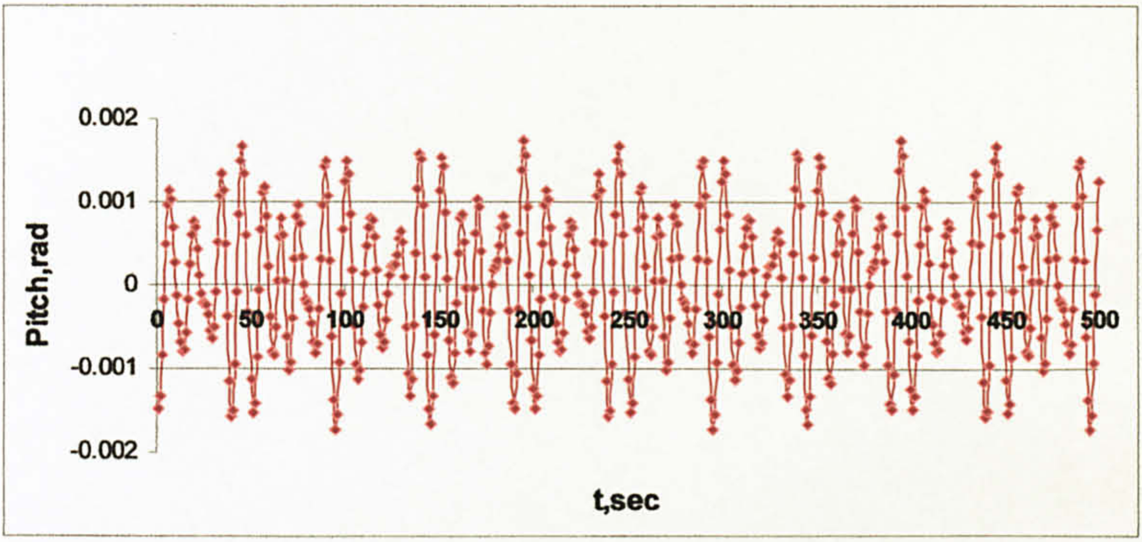

Figure 4.19: Pitch Profile for pitch Response Spectrum at x=0m

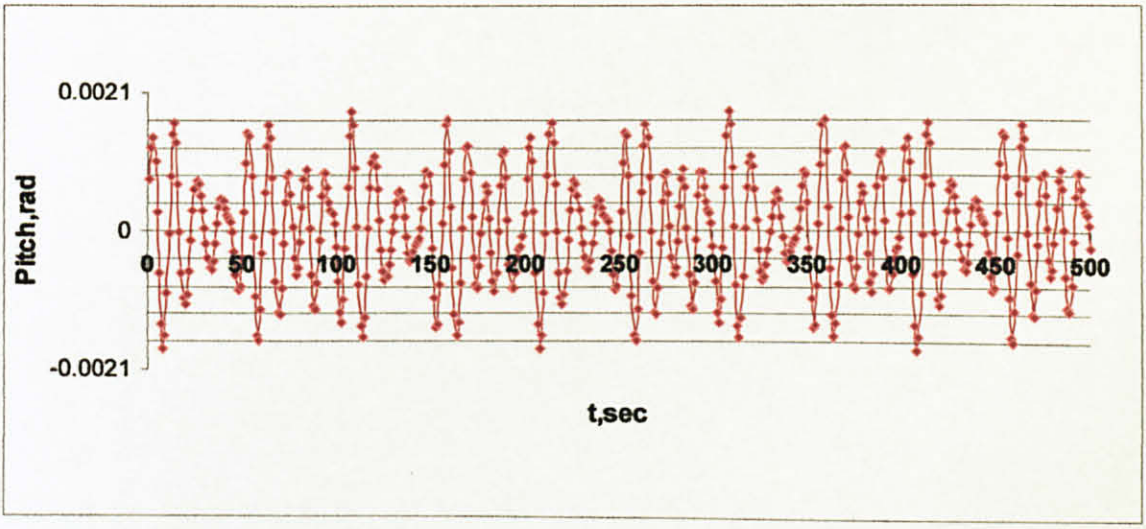

Figure 4.20: Pitch Profile for pitch Response Spectrum at x=125m

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Detailed literature surveys for the hydrodynamic analysis of the FPSO have been done. The literature reviews were taken from updated current technology research on FPSO and mainly related to dynamic analysis for three degree of freedom; surge, heave and pitch. More study for theoretical calculation on Airy Wave and Froude Krylov theory were covered in this project. The environmental data and dimension of FPSO were adapted from FPSO Ruby II project and the approximate dimensions of FPSO at the deep water condition was applied in this project .The numerical calculation on the dynamic analysis of the FPSO using P-M wave spectrum was completed and the maximum motion response of the FPSO in surge, heave and pitch motions were successfully obtained and well discussed in Chapter 4.

Based on the discussion in Chapter 4, the conclusions of the project are:

- A dynamic analysis in frequency domain for obtaining the responses of typical FPSO was successfully completed. The wave forces were calculated using Froude-Krylov theory. The calculation wave forces and moments was really a challenge, as if involves irregular, unique shapes of the FPSO.

- The maximum amplitude is 0.2082 m in surge motion, 0.247 m in heave motion and 0.00049 rad in pitch motion were obtained to regular wave with maximum design wave height of 9.6m.

- Whilst for a P-M spectrum wave of significant height of 4.9 m, the maximum value for surge is 1.14 m; 0.84 m for heave and about 0.00125 rad in pitch motion was successfully obtained in the result analysis.

- The motion responses were within the actual practical limits reported in literature review. Hence, this type of frequency domain analysis can be effectively made use for preliminary design of FPSO.

5.2 RECOMMENDATIONS

Based on the conclusion obtained above, several recommendations can be considered in further research and it aims to enhance the study on the hydrodynamic analysis of FPSO. The recommendations are:

- Further study on the multi-direction waves acting on the FPSO that represent the real situation in the sea state
- Incorporate all non-linear effects such as risers and mooring lines by formulating the mooring line stiffness using matrix and solve using time-domain approach
- Consider the ballast tank and lightweight of the hull for stability of FPSO and performs the stability analysis using the StabCAD software for precise weight and buoyancy calculation
- Study on general strength and structural design to determine the maximum levels of sag, hog, shear and bending moments of FPSO during operation in the sea condition
- Further dynamic analysis by considering the collinear effect of wave, wind and current condition instead of only considering the wave forces impact to the FPSO

CHAPTER 6

ECONOMIC BENEFITS

6.1 PROJECT BENEFIT TO INDUSTRY

Since the exploration of hydrocarbon moved to the deeper water level and more distant locations, the floating production system came to be applied in the offshore industry. The structure design and operation of the offshore structure will have extra complication due to oceanic characteristic that subjected to the environmental condition like wave, wind and current. The optimum structure should be designed with optimum operation cost to meet technical and economic needs for deepwater development. Thus, it is important to study the hydrodynamic analysis on the vessel motion responses in the deep water due to regular and random wave conditions. The data analysis gained from this project can be used and fully utilized in the preliminary design of FPSO and indirectly can sustain the development and production of FPSO in the offshore industry.

6.2 COST COMPARISON OF FLOATING AND FIXED STRUCTURES

Basically the floating offshore structures like Tension Leg Platform (TLP), Spar and FPSO are technically economical independent compared to the fixed offshore structures such as fixed jacket platform and Gravity Base Structure. The cost for fixed structures increase exponentially with water depth and have higher maintenance cost. Whilst for the floating structures, the cost is much lower as the water depth increase because the behaviour of the structures are neutrally buoyant and dynamically unrestrained but resisted by mooring strength. Floating structures also can be decommissioned easily and shifted to another location for reuse. As for the fixed structures, decommissioning of the structures will be done as a whole or partly by reversing the installation procedures and require heavy lift equipments. Thus substantial amount of money needs to be allocated for fixed structure to cover for future decommissioning costs.

6.3 COST BENEFIT OF FPSO

FPSO was introduced as one of the floating structures that are most reliable and has the system of weathervaning that let the vessel to rotate freely around the central mooring as responses to the weather direction and minimizes the impact of the environmental force. Mooring and station keeping are the unique aspect of the floating structures that hold the structures from moving by providing the connection between the structures and the sea floor. The mooring system will eradicate the use of steel material required to construct the traditional structure like fixed jacket that are expensive and are not economically viable for the deep water exploration.

FPSO is particularly more effective to be located in deepwater locations because there are no need installation of costly seabed pipeline and eliminating the immense cost of expensive long distance pipelines from the oil well to an onshore terminal. FPSO have the production facilities that not only can stores temporarily the crude oils, but also process oil, gas and water using their own, on-board production plants before offloads periodically using the small ships. The cost efficiency of FPSO makes it good investment in small field that has limited oil reserves, shallow or deep water regions, which will lessen in a few years and do not substantiate the expense of installing a fixed platform. Once the production exhausted, the FPSO can be remote to another location readily.

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APPENDICES

A. PROJECT MILESTONE FOR SEMESTER JULY 2009 AND JANUARY 2010

No.	Details /Weeks	Sem 1 : July 09 (FYP 1)														Sem 2 : Jan 2010 (FYP 2)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	Selection of Project Topic	■	■																										
2	Preliminary Literature Review		■	■	■																								
3	Data Collection			■	■	■	■																						
4	FPSO Dimension						■	■	■																				
5	Drawing in Autocad									■	■	■	■																
6	Submission of Progress Report 1 & 2 (FYP 1)													⌂															
7	Oral Presentation (FYP 1)														⌂														
8	Theoretical Calculation															■	■	■											
9	Forces Calculation																		■	■	■	■							
10	Motion Responses Calculation																					■	■	■					
11	Regular Wave Condition																							■	■				
12	Random Wave Condition																							■	■				
13	Results Analysis																									■			
14	Discussion Analysis																									■			
15	Poster Preparation																									■			
16	Poster Presentation																									■	⌂		
17	Suggestion on improvement method																										■		
18	Submission of Dissertation Report (FYP 2)																											⌂	
19	Final Oral Presentation (FYP 2)																												⌂
20	Submission of Dissertation Hardbound (FYP 2)																												⌂

■ FYP 1 & FYP 2 Key Milestone
⌂ Submission Date/ Dateline

B. CROSS-SECTIONAL AREA AT BOW SIDE

Depth (m) Below MSL	Breadth (m)	Cross-Sectional Area (m^2)
0	45	45.00
-1	44.61	44.61
-2	44.13	44.13
-3	43.56	43.56
-4	42.88	42.88
-5	42.1	42.10
-6	41.2	41.20
-7	40.19	40.19
-8	39.04	39.04
-9	37.76	37.76
-10	36.32	36.32
-11	34.71	34.71
-12	32.89	32.89
-13	30.85	30.85
-14	28.51	28.51
-15	25.81	25.81
-16	22.62	22.62
-17	18.69	18.69
-18	13.36	10.49

C. COEFFICIENT VALUE FOR Ch AND Cv

Inertia force coefficients for basic structures (Chakrabarti, 2001, p.244)

	Force Coefficients	
	Horizontal	Vertical
Hemisphere	1.5	1.1
Sphere	1.5	1.1
Horizontal halfcylinder	2.0	1.1
Horizontal cylinder	2.0	2.0
Rectangular block	1.5	6.0

D. WEIGHT CALCULATION of FPSO

i) Volume of ½ cylinder shape $= \Pi r^2 h/ 2$

$= (\Pi \times 22.5^2 \times 250)/2$

$= 198{,}803.91 \text{ m}^3$

ii) Assume the curvature shape at bow side as ¼ of the oval shape (below the MSL)

Volume of ellipsoid $= 4/3\ xyz$

¼ of ellipsoid, $= 1/3\ \Pi\ xyz$

$= 1/3 \times \Pi \times 22.5\text{m} \times 25\text{m} \times 18\text{m}$

$= 10{,}\ 603 \text{ m}^3$

The total volume of the FPSO is **209, 407m³**

The weight of the FPSO is calculated using the density equation. (ρ= 1030 kg/m³)

Density (ρ) = m/V

$m = \rho V$

$= 1030 \text{ kg/m}^3 \times 209{,}\ 407\text{m}^3$

$= 215{,}\ 689{,}\ 210 \text{ kg}$

= **216 M-kg**

E. WAVE FORCE CALCULATION - SURGE AND HEAVE for x=0m, t =0s

Regular Wave-Froude Krylov Force
Parametric Data for Surge, Heave and Pitch

PI (π)	=	3.1416	
Gravity Accleration (g)	=	9.807	m/s^2
Sea Water Density (ρ)	=	1030	kg/m^3
Water Depth , (d)	=	1200	m
Distance from origin (x)	**=**	**0**	m
Time at x distance (t)	**=**	**0.0**	s
		(varies from t=0s to t=9s)	

Wave Data

Wave Height (H)	=	9.6	m
Wave Period (T)	=	9	s
Wave Length (L)	=	126.4274	m
Wave Frequency (ω)	=	0.6981	rad/s
Wave Number (k)	=	0.0497	
C_H	=	2.00	
C_V	=	1.10	

Calculated Data

kx-ωt (Θ)	**=**	**-6.2122**	
cos Θ	**=**	**0.9975**	
cosh kd	=	3.97E+25	
H/2	=	4.8	m

SURGE

t(s) = 0

Coordinates			y (m)	s (m)	cosh ks	Pressure (P)	Cross Sec.	Fx(N)	Fy
x	z	y					Area (m2)		
0	0	0.00	0	1200	3.97E+25	48485.81	45.00	4.36E+06	2.40E+06
0	-1	0.00	-0.5	1199.5	3.88E+25	47295.83	44.61	4.22E+06	2.32E+06
0	-2	0.00	-1.5	1198.5	3.69E+25	45002.78	44.13	3.97E+06	2.18E+06
0	-3	0.00	-2.5	1197.5	3.51E+25	42820.90	43.56	3.73E+06	2.05E+06
0	-4	0.00	-3.5	1196.5	3.34E+25	40744.80	42.88	3.49E+06	1.92E+06
0	-5	0.00	-4.5	1195.5	3.18E+25	38769.36	42.10	3.26E+06	1.80E+06
0	-6	0.00	-5.5	1194.5	3.02E+25	36889.70	41.20	3.04E+06	1.67E+06
0	-7	0.00	-6.5	1193.5	2.88E+25	35101.17	40.19	2.82E+06	1.55E+06
0	-8	0.00	-7.5	1192.5	2.74E+25	33399.35	39.04	2.61E+06	1.43E+06
0	-9	0.00	-8.5	1191.5	2.60E+25	31780.04	37.76	2.40E+06	1.32E+06
0	-10	0.00	-9.5	1190.5	2.48E+25	30239.24	36.32	2.20E+06	1.21E+06
0	-11	0.00	-10.5	1189.5	2.36E+25	28773.15	34.71	2.00E+06	1.10E+06
0	-12	0.00	-11.5	1188.5	2.24E+25	27378.13	32.89	1.80E+06	9.91E+05
0	-13	0.00	-12.5	1187.5	2.14E+25	26050.75	30.85	1.61E+06	8.84E+05
0	-14	0.00	-13.5	1186.5	2.03E+25	24787.73	28.51	1.41E+06	7.77E+05
0	-15	0.00	-14.5	1185.5	1.93E+25	23585.94	25.81	1.22E+06	6.70E+05
0	-16	0.00	-15.5	1184.5	1.84E+25	22442.42	22.62	1.02E+06	5.58E+05
0	-17	0.00	-16.5	1183.5	1.75E+25	21354.34	18.69	7.98E+05	4.39E+05
0	-18	0.00	-17.5	1182.5	1.67E+25	20319.01	10.49	4.26E+05	2.34E+05

Total Forces from Aft Side and Bow Side Fx (Wave Angles varies from 0°, 15°, 30°, 45°, 60° ,75° and 90° degree)

Time(s)	Angle(degree)	Aft Side	Bow							
	Depth (m)		0°				15°			
		Fx(N)	Fy=Fsin Θ	Fy'=Fycos45	Fx= Fcos Θ	Fx'=Fxcos45	Fy=Fsin Θ	Fy'=Fycos45	Fx= Fcos Θ	Fx'=Fxcos45
0	0	4363722.72	0.00	0.00	4363722.72	2292359.50	2837675.82	1490693.51	-3315067.41	-1741477.80
	-1	4219734.07	0.00	0.00	4219734.07	2216719.09	2744041.75	1441505.47	-3205680.97	-1684014.70
	-2	3971945.10	0.00	0.00	3971945.10	2086550.10	2582907.60	1356858.16	-3017438.68	-1585126.89
	-3	3730556.59	0.00	0.00	3730556.59	1959743.41	2425935.59	1274397.31	-2834058.75	-1488793.38
	-4	3494274.26	0.00	0.00	3494274.26	1835619.10	2272284.06	1193680.78	-2654557.92	-1394497.65
	-5	3264380.38	0.00	0.00	3264380.38	1714850.79	2122786.87	1115146.62	-2479910.32	-1302751.42
	-6	3039711.25	0.00	0.00	3039711.25	1596827.16	1976687.26	1038397.28	-2309231.89	-1213090.29
	-7	2821431.90	0.00	0.00	2821431.90	1482160.22	1834742.85	963830.77	-2143407.71	-1125979.20
	-8	2607821.29	0.00	0.00	2607821.29	1369945.86	1695834.47	890859.14	-1981130.31	-1040731.31
	-9	2400028.80	0.00	0.00	2400028.80	1260787.90	1560709.55	819875.04	-1823272.87	-957805.33
	-10	2196578.66	0.00	0.00	2196578.66	1153911.07	1428408.39	750374.34	-1668714.25	-876612.29
	-11	1997431.91	0.00	0.00	1997431.91	1049294.90	1298905.68	682343.72	-1517424.88	-797136.66
	-12	1800933.58	0.00	0.00	1800933.58	946070.01	1171125.21	615217.82	-1368147.47	-718717.95
	-13	1607331.45	0.00	0.00	1607331.45	844366.55	1045228.09	549081.30	-1221070.27	-641455.06
	-14	1413396.27	0.00	0.00	1413396.27	742488.14	919114.41	482831.01	-1073740.06	-564059.27
	-15	1217506.20	0.00	0.00	1217506.20	639582.78	791729.47	415912.90	-924924.74	-485883.30
	-16	1015294.95	0.00	0.00	1015294.95	533356.76	660233.96	346835.42	-771307.30	-405184.69
	-17	798225.10	0.00	0.00	798225.10	419325.20	519076.08	272682.08	-606401.96	-318556.28
	-18	426292.82	0.00	0.00	426292.82	223940.99	277213.04	145626.10	-323849.50	-170125.26

30°				45°			
Fy=Fsin Θ	Fy'=Fycos45	Fx= Fcos Θ	Fx'=Fxcos45	Fy=Fsin Θ	Fy'=Fycos45	Fx= Fcos Θ	Fx'=Fxcos45
-4311496.05	-2264923.68	673110.56	353599.78	3713107.04	1950576.78	2292359.50	1204226.85
-4169230.70	-2190188.56	650900.10	341932.13	3590586.59	1886214.09	2216719.09	1164491.28
-3924407.37	-2061577.48	612678.29	321853.38	3379742.09	1775452.83	2086550.10	1096110.65
-3685907.88	-1936288.46	575443.76	302293.26	3174343.75	1667552.57	1959743.41	1029496.30
-3452453.47	-1813649.72	538996.87	283146.91	2973290.28	1561934.76	1835619.10	964291.08
-3225311.05	-1694326.82	503535.41	264518.22	2777672.77	1459172.59	1714850.79	900848.83
-3003330.84	-1577715.73	468879.87	246312.90	2586501.01	1358745.86	1596827.16	838848.42
-2787663.94	-1464421.17	435209.96	228625.36	2400766.35	1261175.35	1482160.22	778611.35
-2576609.90	-1353549.84	402260.21	211316.14	2219004.32	1165691.76	1369945.86	719662.69
-2371304.36	-1245698.32	370207.92	194478.36	2042192.97	1072808.87	1260787.90	662319.61
-2170289.18	-1140100.63	338825.44	177992.46	1869076.52	981866.99	1153911.07	606174.86
-1973525.90	-1036736.55	308106.77	161855.26	1699621.85	892848.73	1049294.90	551217.69
-1779379.33	-934747.09	277796.62	145932.67	1532420.73	805014.30	946070.01	496991.38
-1588094.30	-834260.86	247933.21	130244.76	1367683.99	718474.47	844366.55	443564.32
-1396480.21	-733601.76	218018.42	114529.87	1202663.87	631785.78	742488.14	390045.35
-1202934.62	-631928.01	187802.10	98656.57	1035980.31	544223.24	639582.78	335986.90
-1003143.52	-526973.35	156610.72	82271.05	863918.05	453835.15	533356.76	280184.04
-788671.64	-414306.55	123127.38	64681.52	679212.55	356805.29	419325.20	220280.75
-421190.79	-221260.78	65756.29	34543.22	362734.06	190552.18	223940.99	117641.13

60°				75°			
Fy=Fsin Θ	Fy'=Fycos45	Fx= Fcos Θ	Fx'=Fxcos45	Fy=Fsin Θ	Fy'=Fycos45	Fx= Fcos Θ	Fx'=Fxcos45
-1326763.50	-696978.04	-4145612.71	-2177781.51	-1687915.33	-886699.04	4012150.04	2107670.64
-1282984.62	-673980.03	-4008820.97	-2105921.81	-1632219.62	-857440.86	3879762.14	2038124.36
-1207645.89	-634402.94	-3773417.13	-1982258.99	-1536373.29	-807090.67	3651936.82	1918442.72
-1134253.17	-595848.13	-3544093.84	-1861790.42	-1443002.70	-758041.05	3429996.29	1801852.47
-1062412.96	-558108.89	-3319621.50	-1743870.17	-1351607.21	-710028.99	3212750.56	1687728.51
-992515.11	-521390.01	-3101218.31	-1629138.17	-1262682.82	-663315.05	3001378.57	1576690.16
-924205.82	-485505.64	-2887778.71	-1517013.66	-1175779.39	-617662.77	2794810.39	1468175.35
-857839.31	-450641.85	-2680409.52	-1408078.06	-1091347.57	-573308.87	2594117.18	1362746.80
-792892.29	-416523.76	-2477475.71	-1301472.47	-1008721.64	-529903.66	2397716.57	1259573.24
-729714.24	-383334.94	-2280069.23	-1197770.50	-928346.20	-487680.67	2206665.33	1159209.82
-667856.46	-350839.68	-2086788.04	-1096235.64	-849650.41	-446340.04	2019606.58	1060943.75
-607307.09	-319031.77	-1897595.16	-996848.46	-772619.20	-405873.85	1836504.53	964756.21
-547562.96	-287646.86	-1710918.31	-898783.01	-696612.41	-365945.82	1655837.50	869847.85
-488699.41	-256724.54	-1526992.91	-802162.95	-621725.89	-326606.28	1477833.34	776338.35
-429734.59	-225749.03	-1342751.11	-705376.69	-546710.55	-287199.07	1299522.97	682667.99
-370175.40	-194461.28	-1156652.12	-607614.79	-470939.04	-247394.63	1119415.20	588053.42
-308694.29	-162163.90	-964547.92	-506698.23	-392722.46	-206305.74	933495.54	490385.73
-242695.51	-127493.29	-758327.77	-398366.25	-308758.48	-162197.62	733914.38	385541.36
-129611.75	-68087.90	-404985.61	-212747.85	-164892.74	-86621.78	391947.62	205898.71

90°				Total Forces		Total Forces
Fy=Fsin Θ	**Fy'=Fycos45**	**Fx= Fcos Θ**	**Fx'=Fxcos45**	**∑Fx (N)**	**∑Fy (N)**	**(M-N)**
3891341.26	2044207.13	-1950351.07	-1024562.30	**3.57E+06**	**9.49E+06**	**10.14**
3762939.66	1976754.94	-1885995.83	-990755.08	**3.45E+06**	**9.18E+06**	**9.80**
3541974.33	1860677.00	-1775247.39	-932576.49	**3.25E+06**	**8.64E+06**	**9.23**
3326716.59	1747597.38	-1667359.62	-875900.67	**3.05E+06**	**8.11E+06**	**8.67**
3116012.28	1636909.77	-1561754.03	-820423.73	**2.86E+06**	**7.60E+06**	**8.12**
2911004.87	1529214.87	-1459003.74	-766446.75	**2.67E+06**	**7.10E+06**	**7.58**
2710656.60	1423967.52	-1358588.63	-713696.48	**2.49E+06**	**6.61E+06**	**7.06**
2516006.41	1321713.49	-1261029.42	-662446.48	**2.31E+06**	**6.13E+06**	**6.56**
2325519.57	1221646.56	-1165556.88	-612292.66	**2.13E+06**	**5.67E+06**	**6.06**
2140221.02	1124305.16	-1072684.73	-563504.88	**1.96E+06**	**5.22E+06**	**5.58**
1958794.75	1028997.95	-981753.38	-515736.64	**1.80E+06**	**4.78E+06**	**5.10**
1781206.03	935706.69	-892745.42	-468978.80	**1.63E+06**	**4.34E+06**	**4.64**
1605979.02	843656.09	-804921.15	-422842.78	**1.47E+06**	**3.92E+06**	**4.18**
1433334.69	752962.23	-718391.34	-377386.77	**1.32E+06**	**3.49E+06**	**3.73**
1260393.38	662112.36	-631712.67	-331852.56	**1.16E+06**	**3.07E+06**	**3.28**
1085708.78	570346.70	-544160.26	-285859.35	**9.96E+05**	**2.65E+06**	**2.83**
905387.30	475619.86	-453782.64	-238382.00	**8.31E+05**	**2.21E+06**	**2.36**
711815.68	373932.43	-356764.00	-187415.97	**6.53E+05**	**1.74E+06**	**1.85**
380145.79	199698.94	-190530.13	-100089.67	**3.49E+05**	**9.27E+05**	**0.99**

Time(s)	**Total Forces (M-N)**
0	107.77
1	87.48
2	26.26
3	47.25
4	98.65
5	103.89
6	60.52
7	11.17
8	77.63
9	107.77
Max Force (M-N)	**107.77**

HEAVE

t(s) = 0

Coordinates			y (m)	s (m)	cosh ks	Pressure (P)	Cross Sec.	Fx(N)	Fy
x	z	y					Area (m2)		
0	0	0.00	0	1200	3.97E+25	48485.81	45.00	4.36E+06	2.40E+06
0	-1	0.00	-0.5	1199.5	3.88E+25	47295.83	44.61	4.22E+06	2.32E+06
0	-2	0.00	-1.5	1198.5	3.69E+25	45002.78	44.13	3.97E+06	2.18E+06
0	-3	0.00	-2.5	1197.5	3.51E+25	42820.90	43.56	3.73E+06	2.05E+06
0	-4	0.00	-3.5	1196.5	3.34E+25	40744.80	42.88	3.49E+06	1.92E+06
0	-5	0.00	-4.5	1195.5	3.18E+25	38769.36	42.10	3.26E+06	1.80E+06
0	-6	0.00	-5.5	1194.5	3.02E+25	36889.70	41.20	3.04E+06	1.67E+06
0	-7	0.00	-6.5	1193.5	2.88E+25	35101.17	40.19	2.82E+06	1.55E+06
0	-8	0.00	-7.5	1192.5	2.74E+25	33399.35	39.04	2.61E+06	1.43E+06
0	-9	0.00	-8.5	1191.5	2.60E+25	31780.04	37.76	2.40E+06	1.32E+06
0	-10	0.00	-9.5	1190.5	2.48E+25	30239.24	36.32	2.20E+06	1.21E+06
0	-11	0.00	-10.5	1189.5	2.36E+25	28773.15	34.71	2.00E+06	1.10E+06
0	-12	0.00	-11.5	1188.5	2.24E+25	27378.13	32.89	1.80E+06	9.91E+05
0	-13	0.00	-12.5	1187.5	2.14E+25	26050.75	30.85	1.61E+06	8.84E+05
0	-14	0.00	-13.5	1186.5	2.03E+25	24787.73	28.51	1.41E+06	7.77E+05
0	-15	0.00	-14.5	1185.5	1.93E+25	23585.94	25.81	1.22E+06	6.70E+05
0	-16	0.00	-15.5	1184.5	1.84E+25	22442.42	22.62	1.02E+06	5.58E+05
0	-17	0.00	-16.5	1183.5	1.75E+25	21354.34	18.69	7.98E+05	4.39E+05
0	-18	0.00	-17.5	1182.5	1.67E+25	20319.01	10.49	4.26E+05	2.34E+05

Total Forces from Bottom Side and Bow Side Fy (Wave Angles varies from 0°, 15°, 30°, 45°, 60° ,75° and 90° degree)

Time(s)	Angle(degree)	Bottom Side							
	Depth (m)								
		Fy(N)	Fycos0°(N)	Fycos15°(N)	Fycos30°(N)	Fycos45°(N)	Fycos60°(N)	Fycos75°(N)	Fycos90°(N)
0	0	13333597.20	13333597.20	-1.01E+07	2.06E+06	7.00E+06	-1.27E+07	12290260.15	-5974433.11
	-1	13006353.60	13006353.60	-9.88E+06	2.01E+06	6.83E+06	-1.24E+07	11988622.94	-5827803.89
	-2	12375763.69	12375763.69	-9.40E+06	1.91E+06	6.50E+06	-1.18E+07	11407375.89	-5545253.19
	-3	11775746.81	11775746.81	-8.95E+06	1.82E+06	6.19E+06	-1.12E+07	10854309.57	-5276401.45
	-4	11204820.68	11204820.68	-8.51E+06	1.73E+06	5.89E+06	-1.07E+07	10328057.68	-5020584.52
	-5	10661574.88	10661574.88	-8.10E+06	1.64E+06	5.60E+06	-1.02E+07	9827320.18	-4777170.41
	-6	10144667.39	10144667.39	-7.71E+06	1.56E+06	5.33E+06	-9.66E+06	9350860.05	-4545557.80
	-7	9652821.25	9652821.25	-7.33E+06	1.49E+06	5.07E+06	-9.19E+06	8897500.24	-4325174.52
	-8	9184821.39	9184821.39	-6.98E+06	1.42E+06	4.82E+06	-8.75E+06	8466120.77	-4115476.13
	-9	8739511.66	8739511.66	-6.64E+06	1.35E+06	4.59E+06	-8.32E+06	8055655.97	-3915944.59
	-10	8315791.99	8315791.99	-6.32E+06	1.28E+06	4.37E+06	-7.92E+06	7665091.83	-3726086.99
	-11	7912615.61	7912615.61	-6.01E+06	1.22E+06	4.16E+06	-7.54E+06	7293463.49	-3545434.29
	-12	7528986.52	7528986.52	-5.72E+06	1.16E+06	3.96E+06	-7.17E+06	6939852.89	-3373540.22
	-13	7163957.01	7163957.01	-5.44E+06	1.11E+06	3.76E+06	-6.82E+06	6603386.47	-3209980.12
	-14	6816625.30	6816625.30	-5.18E+06	1.05E+06	3.58E+06	-6.49E+06	6283233.03	-3054349.95
	-15	6486133.35	6486133.35	-4.93E+06	1.00E+06	3.41E+06	-6.18E+06	5978601.65	-2906265.23
	-16	6171664.72	6171664.72	-4.69E+06	9.52E+05	3.24E+06	-5.88E+06	5688739.79	-2765360.13
	-17	5872442.54	5872442.54	-4.46E+06	9.06E+05	3.08E+06	-5.59E+06	5412931.36	-2631286.56
	-18	5587727.61	5587727.61	-4.24E+06	8.62E+05	2.94E+06	-5.32E+06	5150495.02	-2503713.32

0° Bow				15°Bow			
Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45	Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45
0.00	0.00	2400047.50	1260797.72	1560721.70	819881.43	-1823287.07	-957812.79
0.00	0.00	2320853.74	1219195.50	1509222.96	792828.01	-1763124.53	-926208.09
0.00	0.00	2184569.81	1147602.56	1420599.18	746271.99	-1659591.28	-871819.79
0.00	0.00	2051806.12	1077858.87	1334264.57	700918.52	-1558732.31	-818836.36
0.00	0.00	1921850.84	1009590.51	1249756.23	656524.43	-1460006.86	-766973.70
0.00	0.00	1795409.21	943167.94	1167532.78	613330.64	-1363950.68	-716513.28
0.00	0.00	1671841.19	878254.94	1087177.99	571118.51	-1270077.54	-667199.66
0.00	0.00	1551787.54	815188.12	1009108.57	530106.92	-1178874.24	-619288.56
0.00	0.00	1434301.71	753470.23	932708.96	489972.53	-1089621.67	-572402.22
0.00	0.00	1320015.84	693433.35	858390.25	450931.27	-1002800.08	-526792.93
0.00	0.00	1208118.26	634651.09	785624.61	412705.88	-917792.84	-482136.76
0.00	0.00	1098587.55	577112.20	714398.13	375289.04	-834583.68	-438425.16
0.00	0.00	990513.47	520338.50	644118.86	338369.80	-752481.11	-395294.87
0.00	0.00	884032.30	464401.60	574875.45	301994.72	-671588.65	-352800.28
0.00	0.00	777367.95	408368.48	505512.92	265557.06	-590557.04	-310232.60
0.00	0.00	669628.41	351770.53	435451.21	228752.10	-508708.61	-267235.82
0.00	0.00	558412.22	293346.22	363128.68	190759.48	-424219.02	-222851.58
0.00	0.00	439023.80	230628.86	285491.84	149975.14	-333521.08	-175205.96
0.00	0.00	234461.05	123167.55	152467.17	80094.36	-178117.23	-93568.90

30°Bow				45°Bow			
Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45	Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45
-2371322.83	-1245708.02	370210.81	194479.88	2042208.87	1072817.23	1260797.72	662324.77
-2293076.89	-1204603.71	357995.05	188062.67	1974822.62	1037417.75	1219195.50	640470.21
-2158424.05	-1133867.62	336973.06	177019.36	1858858.15	976499.06	1147602.56	602860.86
-2027249.34	-1064958.65	316494.07	166261.29	1745889.06	917153.91	1077858.87	566222.97
-1898849.41	-997507.35	296448.28	155730.80	1635309.66	859064.12	1009590.51	530360.09
-1773921.08	-931879.75	276944.47	145485.02	1527720.02	802544.92	943167.94	495466.86
-1651831.96	-867743.65	257883.93	135472.10	1422575.56	747310.22	878254.94	461366.63
-1533215.17	-805431.64	239365.48	125743.95	1320421.49	693646.44	815188.12	428236.24
-1417135.45	-744452.41	221243.12	116223.87	1220452.38	641130.47	753470.23	395814.48
-1304217.40	-685134.08	203614.36	106963.10	1123206.13	590044.88	693433.35	364275.79
-1193659.05	-627055.34	186353.99	97895.85	1027992.09	540026.85	634651.09	333396.17
-1085439.24	-570205.10	169458.72	89020.39	934792.02	491066.80	577112.20	303169.73
-978658.63	-514110.90	152788.14	80262.97	842831.40	442757.87	520338.50	273345.26
-873451.86	-458843.47	136363.26	71634.62	752226.20	395160.96	464401.60	243960.37
-768064.12	-403480.97	119910.13	62991.43	661465.13	347482.18	408368.48	214524.94
-661614.04	-347560.40	103291.15	54261.11	569789.17	299322.78	351770.53	184792.79
-551728.94	-289835.34	86135.90	45249.08	475154.93	249609.33	293346.22	154101.22
-433769.40	-227868.61	67720.06	35574.84	373566.90	196242.91	230628.86	121154.41
-231654.93	-121693.43	36165.96	18998.77	199503.73	104803.70	123167.55	64702.62

60°Bow				75°Bow			
Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45	Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45
-731559.97	-384304.54	-2285836.39	-1200800.12	-930694.34	-488914.20	2212246.83	1162141.90
-707420.87	-371623.74	-2210411.22	-1161177.62	-899984.46	-472781.63	2139249.88	1123795.00
-665880.08	-349801.45	-2080612.64	-1092991.57	-847136.05	-445019.20	2013629.99	1057804.11
-625412.30	-328542.83	-1954166.79	-1026566.78	-795652.73	-417973.88	1891254.90	993517.79
-585800.55	-307733.91	-1830395.69	-961547.10	-745258.46	-391500.66	1771468.45	930591.33
-547259.80	-287487.60	-1709971.04	-898285.39	-696226.72	-365743.21	1654920.72	869366.24
-509594.95	-267701.43	-1592283.25	-836461.40	-648309.31	-340571.14	1541021.74	809532.60
-473001.33	-248478.00	-1477942.60	-776395.75	-601754.71	-316114.98	1430362.14	751400.68
-437190.39	-229665.73	-1366047.56	-717614.82	-556195.86	-292181.92	1322069.42	694512.14
-402354.85	-211365.85	-1257200.22	-660434.92	-511877.90	-268900.72	1216726.28	639173.07
-368247.28	-193448.39	-1150627.51	-604449.93	-468486.07	-246106.04	1113584.54	584990.45
-334861.15	-175909.93	-1046309.04	-549649.15	-426012.08	-223793.51	1012624.47	531953.90
-301919.03	-158604.70	-943377.88	-495577.15	-384102.93	-201777.72	913007.05	479622.68
-269462.43	-141554.54	-841963.83	-442302.12	-342811.49	-180086.41	814857.89	428062.77
-236950.01	-124475.05	-740375.33	-388935.44	-301449.01	-158357.80	716539.89	376414.16
-204109.85	-107223.39	-637762.79	-335030.82	-259669.60	-136410.15	617230.83	324244.93
-170209.98	-89415.04	-531839.05	-279386.75	-216542.01	-113754.28	514717.18	270392.25
-133819.12	-70298.13	-418131.97	-219653.92	-170245.37	-89433.64	404670.75	212582.44
-71466.22	-37542.78	-223303.75	-117306.37	-90919.69	-47762.11	216114.77	113529.84

90°Bow				Total Forces			
				Bow		Bottom	Total Forces
Fy=Fsin θ	Fy'=Fycos45	Fx= Fcos θ	Fx'=Fxcos45	∑Fx (N)	∑Fy (N)	∑Fy (N)	(M-N)
2145634.45	1127148.96	-1075397.96	-564930.20	4.31E+05	5.23E+06	1.57E+06	6.81E+00
2074835.50	1089956.71	-1039913.33	-546289.34	4.17E+05	5.06E+06	1.53E+06	6.60E+00
1952998.12	1025952.86	-978848.09	-514210.43	3.92E+05	4.76E+06	1.46E+06	6.23E+00
1834307.83	963602.24	-919360.19	-482960.12	3.68E+05	4.47E+06	1.39E+06	5.87E+00
1718128.24	902570.54	-861130.66	-452370.87	3.45E+05	4.19E+06	1.32E+06	5.52E+00
1605089.84	843188.99	-804475.50	-422608.67	3.22E+05	3.91E+06	1.25E+06	5.18E+00
1494620.44	785156.98	-749107.93	-393522.87	3.00E+05	3.64E+06	1.19E+06	4.85E+00
1387292.89	728775.46	-695315.06	-365264.29	2.79E+05	3.38E+06	1.14E+06	4.53E+00
1282260.94	673599.87	-642672.75	-337610.13	2.57E+05	3.13E+06	1.08E+06	4.22E+00
1180089.76	619927.10	-591464.27	-310709.19	2.37E+05	2.88E+06	1.03E+06	3.91E+00
1080053.69	567375.95	-541325.92	-284370.41	2.17E+05	2.63E+06	9.79E+05	3.62E+00
982133.61	515936.38	-492248.10	-258588.75	1.97E+05	2.39E+06	9.31E+05	3.33E+00
885515.73	465180.89	-443822.95	-233149.96	1.78E+05	2.16E+06	8.86E+05	3.05E+00
790321.92	415173.48	-396111.55	-208086.11	1.59E+05	1.93E+06	8.43E+05	2.77E+00
694964.35	365080.06	-348318.07	-182979.14	1.40E+05	1.69E+06	8.02E+05	2.50E+00
598645.56	314481.68	-300042.82	-157619.09	1.20E+05	1.46E+06	7.63E+05	2.23E+00
499218.66	262250.54	-250209.78	-131440.70	1.00E+05	1.22E+06	7.26E+05	1.95E+00
392485.82	206181.43	-196714.98	-103338.71	7.88E+04	9.57E+05	6.91E+05	1.65E+00
209607.40	110111.37	-105055.81	-55188.13	4.21E+04	5.11E+05	6.58E+05	1.17E+00

Time(s)	Total Forces (M-N)
0	75.99
1	58.21
2	13.20
3	38.00
4	71.41
5	71.41
6	38.00
7	13.20
8	58.21
9	75.99
Max Force (M-N)	75.99

F. MOMENT CALCULATION- PITCH for x=0m, t =0s

	0	1	2	3	4	5	6	7	8	9	**Max Force (M-N)**	**Arm Distance(m)**	**Moment (M-Nm)**
0	13.09269993	10.02959	2.273523	6.54635	12.30311351	12.30311	6.54635	2.273523	10.02959	13.0927	**13.0597688**	**-4.85**	**-63.33987866**
-1	12.66068342	9.698646	2.198505	6.330342	11.89715078	11.89715	6.330342	2.198505	9.698646	12.66068	**12.62883891**	**-3.85**	**-48.6210298**
-2	11.91722955	9.129127	2.069405	5.958615	11.19853267	11.19853	5.958615	2.069405	9.129127	11.91723	**11.88725499**	**-2.85**	**-33.87867673**
-3	11.19297927	8.57432	1.94364	5.59649	10.51796003	10.51796	5.59649	1.94364	8.57432	11.19298	**11.16482637**	**-1.85**	**-20.65492879**
-4	10.48404935	8.031248	1.820536	5.242025	9.851783806	9.851784	5.242025	1.820536	8.031248	10.48405	**10.45767957**	**0**	**0**
-5	9.794287019	7.502859	1.70076	4.897144	9.203619237	9.203619	4.897144	1.70076	7.502859	9.794287	**9.769652149**	**1.15**	**11.23509997**
-6	9.120200754	6.986479	1.583706	4.5601	8.570185348	8.570185	4.5601	1.583706	6.986479	9.120201	**9.097261365**	**2.15**	**19.55911194**
-7	8.46528608	6.484785	1.469982	4.232643	7.954766862	7.954767	4.232643	1.469982	6.484785	8.465286	**8.443993952**	**3.15**	**26.59858095**
-8	7.824379264	5.993822	1.358689	3.91219	7.352511457	7.352511	3.91219	1.358689	5.993822	7.824379	**7.804699163**	**4.15**	**32.38950153**
-9	7.200928874	5.516232	1.250428	3.600464	6.766659726	6.76666	3.600464	1.250428	5.516232	7.200929	**7.182816893**	**5.15**	**36.991507**
-10	6.590507016	5.048621	1.14443	3.295254	6.19305081	6.193051	3.295254	1.14443	5.048621	6.590507	**6.573930385**	**6.15**	**40.42967187**
-11	5.992996881	4.590902	1.040673	2.996498	5.631574946	5.631575	2.996498	1.040673	4.590902	5.992997	**5.977923125**	**7.15**	**42.74215034**
-12	5.403432899	4.13927	0.938296	2.701716	5.077566022	5.077566	2.701716	0.938296	4.13927	5.403433	**5.389842031**	**8.15**	**43.92721255**
-13	4.822558547	3.694294	0.837429	2.411279	4.53172268	4.531723	2.411279	0.837429	3.694294	4.822559	**4.81042871**	**9.15**	**44.0154227**
-14	4.240684949	3.248553	0.736387	2.120342	3.984940354	3.98494	2.120342	0.736387	3.248553	4.240685	**4.230018658**	**10.15**	**42.93468938**
-15	3.652945958	2.798319	0.634327	1.826473	3.432646361	3.432646	1.826473	0.634327	2.798319	3.652946	**3.643757965**	**11.15**	**40.62790131**
-16	3.046241249	2.333556	0.528974	1.523121	2.862530423	2.86253	1.523121	0.528974	2.333556	3.046241	**3.038579256**	**12.15**	**36.91873796**
-17	2.39495549	1.834642	0.41588	1.197478	2.250522001	2.250522	1.197478	0.41588	1.834642	2.394955	**2.38893163**	**13.15**	**31.41445093**
-18	1.279028096	0.979792	0.222101	0.639514	1.201893263	1.201893	0.639514	0.222101	0.979792	1.279028	**1.275811048**	**14.15**	**18.05272633**

Clockwise	-166.494514
Counterclock	467.8367648
Total Moment (M-Nm)	**301.3422508**

G. CALCULATION OF RAO- Regular Wave for x=125m and t =0s

RAO Surge

Water Depth(m)	1200
Distance from origin(m)	125.0
Time at x distance (s)	0.0
kx-ωt (Θ)	6.212244719
Damping Ratio (ς)	0.05
Inertia Coef, Cm	2
Gravity Accleration (g),m/s2	9.807
Sea Water Density (ρ),kg/m3	1030
Pressure (N-m2)	48363.85512
Cross Section Area(m2)	45.00
Total Force (M-N)	107.7707069
Added Mass (M-kg)	6.216320243
Total Mass(M-kg)	222.2163202
Cross Sec Area-Surge, m2	636.17251
Diameter, Dr	3.38399
Natural Period (Tn),s	206.80000
ωn	0.03038
ω	0.69813
Stiffness,K (M-N/m)	0.20513
Critical Damping, Cc	13.50316
Constant Damping Coef, C	0.67516
(K-mω2)2	1.169E+04
(Cω)2	2.222E-01
((K-mω2)2+(Cω)2)^1/2	1.08101E+02
RAO Surge (m)	0.2077

RAO Heave

Water Depth(m)	1200
Distance from origin(m)	125.0
Time at x distance (s)	0.0
kx-ωt (Θ)	6.212244719
Damping Ratio (ς)	0.05
Inertia Coef, Cm	2
Gravity Accleration (g),m/s2	9.807
Sea Water Density (ρ),kg/m3	1030
Pressure (N-m2)	48363.85512
Cross Section Area(m2)	45.00
Total Force (M-N)	75.79904804
Added Mass (M-kg)	517.7905104
Total Mass(M-kg)	432
Cross Sec Area-Surge, m2	12133.57293
Diameter, Dr	124.29378
Natural Period (Tn),s	10.70000
ωn	0.58721
ω	0.69813
Stiffness,K (M-N/m)	148.96215
Critical Damping, Cc	507.35253
Constant Damping Coef, C	25.36763
(K-mω2)2	3.793E+03
(Cω)2	3.136E+02
((K-mω2)2+(Cω)2)^1/2	6.40851E+01
RAO Heave (m)	0.2464

RAO Pitch

Water Depth(m)	1200
Distance from origin(m)	125
Time at x distance (s)	0
kx-ωt (Θ)	6.212245
Damping Ratio (ς)	0.05
Inertia Coef, Cm	2
Gravity Accleration (g),m/s2	9.807
Sea Water Density (ρ),kg/m3	1030
Total Moment (MN-m)	301.3423
Added Mass (M-kg)	97130
Total Mass(M-kg)	843750
Natural Period (Tn),s	*10.5*
ωn	0.598399
ω	0.698132
Stiffness,K (M-N/m)	336911.1
Critical Damping, Cc	1126043
Constant Damping Coef, C	56302.13
(K-mω2)2	1.48E+10
(Cω)2	1.54E+09
((K-mω2)2+(Cω)2)^1/2	127854.3
RAO Pitch (rad/s)	0.000491

H. CALCULATION of WAVE SPECTRUM at x = -125m

α	0.0081
g	9.807
Hs(m)	4.9
ωo	0.5677
PI	3.1416
fo	0.0903
(α*g^2)/ (2π^4)	0.000499848
△f	0.01
x(m)	-125

f,Hz	T,s	2πf	L,m	k	(f^-5)	(f/fo)^-4	S(f),m-s2	H(n),m	Rn	ε(n)
0.005	200.000	0.031	62433.3011	0.000	3.2E+11	106593.924	0.000	0.000	0.715	4.495
0.015	66.667	0.094	6937.03345	0.001	1316872428	1315.97438	0.000	0.000	0.789	4.957
0.025	40.000	0.157	2497.33204	0.003	102400000	170.550279	0.000	0.000	0.317	1.990
0.035	28.571	0.220	1274.149	0.005	19039685.8	44.395637	0.000	0.000	0.607	3.813
0.045	22.222	0.283	770.781495	0.008	5419228.1	16.2465972	0.000	0.001	0.620	3.897
0.055	18.182	0.346	515.977695	0.012	1986948.23	7.28050847	0.111	0.094	0.988	6.209
0.065	15.385	0.408	369.427817	0.017	861853.038	3.73214959	4.057	0.570	0.744	4.677
0.075	13.333	0.471	277.481338	0.023	421399.177	2.105559	15.153	1.101	0.574	3.609
0.085	11.765	0.534	216.032184	0.029	225374.809	1.27625297	22.851	1.352	0.721	4.527
0.095	10.526	0.597	172.945432	0.036	129235.543	0.8179336	23.238	1.363	0.405	2.544
0.105	9.524	0.660	141.572111	0.044	78352.6166	0.54809428	19.740	1.257	0.788	4.952
0.115	8.696	0.723	118.021363	0.053	49717.6735	0.38090889	15.437	1.111	0.406	2.551
0.125	8.000	0.785	99.8932817	0.063	32768	0.27288045	11.645	0.965	0.335	2.104
0.135	7.407	0.848	85.6423883	0.073	22301.3502	0.20057527	8.675	0.833	0.914	5.745
0.145	6.897	0.911	74.2369811	0.085	15601.2713	0.15070944	6.459	0.719	0.852	5.351
0.155	6.452	0.974	64.9670146	0.097	11177.4184	0.11542122	4.836	0.622	0.357	2.243
0.165	6.061	1.037	57.330855	0.110	8176.7417	0.08988282	3.653	0.541	0.155	0.974
0.175	5.714	1.100	50.9659601	0.123	6092.69947	0.07103302	2.787	0.472	0.991	6.228
0.185	5.405	1.162	45.605041	0.138	4614.67753	0.05687554	2.148	0.415	0.930	5.841
0.195	5.128	1.225	41.0475352	0.153	3546.72032	0.04607592	1.674	0.366	0.348	2.184
0.205	4.878	1.288	37.1405717	0.169	2762.04465	0.0377222	1.317	0.325	0.791	4.969
0.215	4.651	1.351	33.7659822	0.186	2176.74573	0.03117874	1.046	0.289	0.706	4.438
0.225	4.444	1.414	30.8312598	0.204	1734.15299	0.02599456	0.839	0.259	0.067	0.422
0.235	4.255	1.477	28.2631512	0.222	1395.27781	0.02184445	0.679	0.233	0.168	1.055
0.245	4.082	1.539	26.0030408	0.242	1132.84262	0.01849048	0.553	0.210	0.962	6.048
0.255	3.922	1.602	24.003576	0.262	927.468349	0.01575621	0.455	0.191	0.357	2.245
0.265	3.774	1.665	22.2261663	0.283	765.192369	0.01350918	0.376	0.173	0.805	5.060
0.275	3.636	1.728	20.6391078	0.304	635.823435	0.01164881	0.313	0.158	0.692	4.348
0.285	3.509	1.791	19.2161591	0.327	531.833512	0.01009795	0.263	0.145	0.749	4.707
0.295	3.390	1.854	17.9354499	0.350	447.599837	0.00879679	0.221	0.133	0.120	0.753
0.305	3.279	1.916	16.7786351	0.374	378.879235	0.00769862	0.188	0.122	0.474	2.979
0.315	3.175	1.979	15.7302346	0.399	322.438752	0.0067666	0.160	0.113	0.236	1.483
0.325	3.077	2.042	14.7771127	0.425	275.792972	0.00597144	0.137	0.105	0.677	4.255
0.335	2.985	2.105	13.9080644	0.452	237.015072	0.00528973	0.118	0.097	0.111	0.701
0.345	2.899	2.168	13.1134848	0.479	204.59948	0.00470258	0.102	0.090	0.895	5.622
0.355	2.817	2.231	12.3851024	0.507	177.361043	0.00419468	0.088	0.084	0.120	0.753
0.365	2.740	2.293	11.715763	0.536	154.360323	0.00375354	0.077	0.078	0.724	4.548
0.375	2.667	2.356	11.0992535	0.566	134.847737	0.00336889	0.067	0.073	0.397	2.493
0.385	2.597	2.419	10.530157	0.597	118.221469	0.00303228	0.059	0.069	0.368	2.315
0.395	2.532	2.482	10.0037335	0.628	103.995494	0.00273668	0.052	0.064	0.423	2.655

I. MOTION RESPONSES OF FPSO SUBJECTED TO RANDOM WAVE

Surge

f,Hz	0	125	-125
0.005	0.000000	0.000000	0.000000
0.015	0.000000	0.000000	0.000000
0.025	0.000000	0.000000	0.000000
0.035	0.000000	0.000000	0.000000
0.045	0.001624	0.001657	0.001165
0.055	0.124640	0.192725	0.189776
0.065	0.560508	0.795476	0.522068
0.075	1.140855	1.082002	1.090425
0.085	0.667007	0.666837	0.666475
0.095	0.514018	0.513400	0.503179
0.105	0.368922	0.367860	0.358978
0.115	0.257921	0.256068	0.256646
0.125	0.179326	0.179320	0.179320
0.135	0.125220	0.125219	0.124700
0.145	0.088222	0.087023	0.085605
0.155	0.062843	0.060457	0.062800
0.165	0.045295	0.045270	0.045083
0.175	0.033038	0.032713	0.031585
0.185	0.024382	0.024209	0.024382
0.195	0.018200	0.018053	0.017635
0.205	0.013736	0.013634	0.013204
0.215	0.010476	0.009692	0.010441
0.225	0.008072	0.008069	0.007608
0.235	0.006279	0.005555	0.006242
0.245	0.004930	0.004759	0.004558
0.255	0.003905	0.003847	0.003734
0.265	0.003120	0.002723	0.002590
0.275	0.002512	0.002356	0.002510
0.285	0.002038	0.002038	0.002037
0.295	0.001666	0.001635	0.001636
0.305	0.001371	0.001304	0.001338
0.315	0.000116	0.000109	0.000116
0.325	0.000097	0.000093	0.000096
0.335	0.000081	0.000081	0.000081
0.345	0.000068	0.000067	0.000067
0.355	0.000058	0.000055	0.000048
0.365	0.000049	0.000048	0.000046
0.375	0.000042	0.000042	0.000042
0.385	0.000000	0.000000	0.000000
0.395	0.000000	0.000000	0.000000

Heave

f,Hz	0	125	-125
0.005	0	0	0
0.015	0	0	0
0.025	0	0	0
0.035	0	0	0
0.045	0	0	0
0.055	0.01961	0.01955	0.02023
0.065	0.14443	0.14404	0.15032
0.075	0.38307	0.37854	0.39903
0.085	0.84121	0.84099	0.08756
0.095	0.24051	0.24022	0.02453
0.105	0.48406	0.48267	0.04906
0.115	0.17605	0.17479	0.01825
0.125	0.16608	0.16607	0.01730
0.135	0.11717	0.11717	0.01215
0.145	0.09497	0.09368	0.00960
0.155	0.07709	0.07416	0.00802
0.165	0.06279	0.06276	0.00651
0.175	0.05138	0.05088	0.00512
0.185	0.04227	0.04197	0.00440
0.195	0.03497	0.03469	0.00353
0.205	0.02910	0.02023	0.00291
0.215	0.02436	0.02254	0.00253
0.225	0.02051	0.02051	0.00201
0.235	0.01738	0.01537	0.00180
0.245	0.01481	0.01429	0.00143
0.255	0.01269	0.01250	0.00126
0.265	0.01093	0.00954	0.00095
0.275	0.00947	0.00888	0.00099
0.285	0.00824	0.00824	0.00086
0.295	0.00689	0.00679	0.00071
0.305	0.00634	0.00603	0.00064
0.315	0.00560	0.00528	0.00058
0.325	0.00496	0.00480	0.00051
0.335	0.00000	0.00000	0.00000
0.345	0.00000	0.00000	0.00000
0.355	0.00000	0.00000	0.00000
0.365	0.00000	0.00000	0.00000
0.375	0.00000	0.00000	0.00000
0.385	0.00000	0.00000	0.00000
0.395	0.00000	0.00000	0.00000

Pitch

f,Hz	0	125	-125
0.005	0.0000000	0.0000000	0.0000000
0.015	0.0000000	0.0000000	0.0000000
0.025	0.0000000	0.0000000	0.0000000
0.035	0.0000000	0.0000000	0.0000000
0.045	0.0000004	0.0000004	0.0000003
0.055	0.0001135	0.0001233	0.0001214
0.065	0.0004838	0.0006826	0.0005163
0.075	0.0012459	0.0011778	0.0011951
0.085	0.0008877	0.0008875	0.0008870
0.095	0.0007959	0.0007949	0.0007791
0.105	0.0006414	0.0006396	0.0006241
0.115	0.0004867	0.0004826	0.0004843
0.125	0.0003550	0.0003550	0.0003550
0.135	0.0002506	0.0002425	0.0002495
0.145	0.0001710	0.0001686	0.0001659
0.155	0.0001117	0.0001074	0.0001116
0.165	0.0000682	0.0000682	0.0000679
0.175	0.0000369	0.0000365	0.0000353
0.185	0.0000146	0.0000145	0.0000146
0.195	-0.0000009	-0.0000009	-0.0000009
0.205	-0.0000115	-0.0000114	-0.0000114
0.215	-0.0000184	-0.0000171	-0.0000171
0.225	-0.0000228	-0.0000228	-0.0000228
0.235	-0.0000252	-0.0000223	-0.0000223
0.245	-0.0000263	-0.0000254	-0.0000254
0.255	-0.0000265	-0.0000261	-0.0000261
0.265	-0.0000261	-0.0000228	-0.0000228
0.275	-0.0000253	-0.0000237	-0.0000237
0.285	-0.0000242	-0.0000241	-0.0000241
0.295	-0.0000229	-0.0000225	-0.0000225
0.305	-0.0000216	-0.0000205	-0.0000205
0.315	-0.0000203	-0.0000191	-0.0000191
0.325	-0.0000189	-0.0000183	-0.0000183
0.335	-0.0000177	-0.0000176	-0.0000176
0.345	-0.0000165	-0.0000161	-0.0000161
0.355	-0.0000153	-0.0000145	-0.0000145
0.365	-0.0000143	-0.0000139	-0.0000139
0.375	-0.0000133	-0.0000132	-0.0000132
0.385	0.0000000	0.0000000	0.0000000
0.395	0.0000000	0.0000000	0.0000000